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Volume 4 2018
Including lecture articles from the AGM 2017, the Edinburgh Symposium 2017, OUGS Members' field trip reports, the Annual Report for 2017, and the 2017 Moyra Eldridge Photographic Competition winning and highly commended photographs

Edited and designed by:
Dr David M. Jones
41 Blackburn Way,
Godalming, Surrey GU7 1JY
e-mail: proceedings@ougs.org

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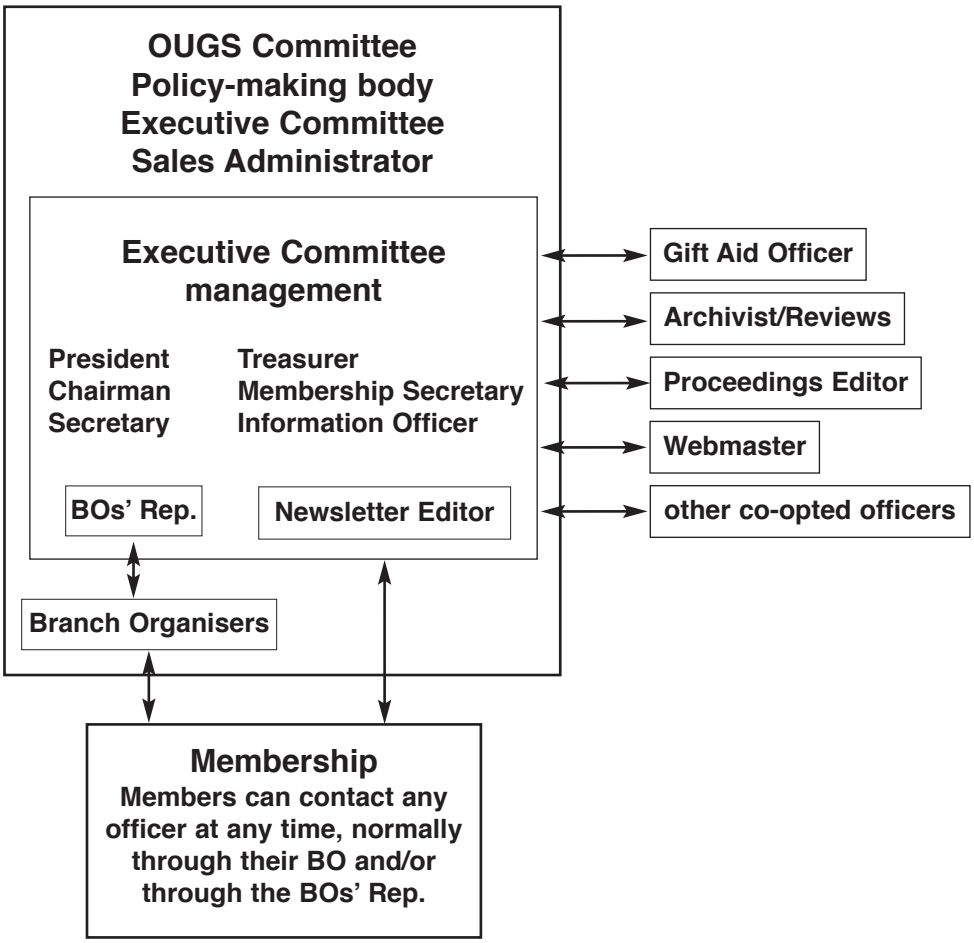

Editorial:

Dear readers,

This issue has articles from the speakers at our April 2017 AGM weekend in Milton Keynes; and at our August 2017 Symposium in Edinburgh, entitled, 'A Festival of Geodiversity'; plus contributions from OUGS Members and others.

At the AGM weekend Dr Luke Mander (OU) summarised the story of the diversity of life on Earth and the effects of mass extinction events.

Unfortunately, Dr Clive Oppenheimer was unable to write up his interesting Geoff Brown Memorial Lecture on the Mt Erebus volcano on Ross Island, Antarctica. Interested readers can find a short summary, with a few photographs, in the Severnside Branch newsletter Sabrina Times *(July 2017, 8–9; author unidentified).*

The lectures at the 2017 OUGS Symposium, and the subsequent articles from them, as always, range widely in subject matter and application to Earth Sciences. Friday evening's lecture by Dr Simon Cuthbert (U West of Scotland) started our Symposium with an intersting description of the tectonics and metals of the Scottish Southern Uplands.

Saturday's lectures began with a veritable tour de force from Dr Maarten Krabbendam (BGS) on the Grenville Orogen and the Torridon Moine Thrust — all about foreland basins.

Next, Dr Tim Kearsey (BGS) told us about the TW:eed Project explorations in the Scottish Borders and filling in 'Romer's gap', that annoying lacuna in the evidence for tetrapod evolution during the first 15 million years of the Carboniferous (Tournaisian) — remarkable finds that enhance our understanding of the evolution of life on land.

Dr Paul Mellon (Transport Scotland) then filled us in on the intricate process of building a bridge — the new Queensferry Crossing of the Firth of Forth; on the geology that needs to be done before the first engineering designs are even thought about.

Sunday's lectures began with another entertaining description by Dr Neil Clark (Hunterian Museum, U Glasgow) of his continuing quest for dinosaurs in Scotland. Like the members of TW:eed Project's discoveries of early tetrapods, on the Isle of Skye Dr Clark has discovered some of the rarest Jurassic dinosaurs. Dr Clark has the distinction of being in the Guinness Book of Records *for some of his discoveries.*

Prof. John Underhill (Harriot-Watt U) brought us back to big earth movements and structures, describing new research and understanding of the evolution of eastern Scotland's Midland Valley Basin.

Next came Dr Ian Williamson's (OUGS) fascinating lecture on Scotland's Palaeocene lava fields, featuring an abundance of stunning photographs, including huge fossilised trees!

Mr David Jarman followed with a detailed summary of his study of Rock Slope Failure in the UK, of which he is a leading researcher. His talk was a tour of Scotland and its 'RSFs'. It is indeed unfortunate that Mr Jarman was unable to complete a write-up of his lecture; and also unfortunate that a transcription of his lecture unavoidably contains too many inaudible and undeciferable sections, making it impossible to provide a publishable edited version of it.

Rosalind Garton (geoHeritage Fife) reminded us of the keen interest in geology of non-professionals. With Richard Batchelor she runs geoHeritage Fife, providing dissemination of local geological excursions, information and geology trail publications to engage 'the public' with what's beneath their feet.

To round off our Symposium weekend, Dr Graham Leslie (BGS) gave a superlative example of recycling! He and his colleagues' hard work is transforming the no-longer-working Spireslack opencast coal mine in East Ayrshire into a national asset as a geopark, turning a 'scar on the landscape' into a valuable Earth Sciences teaching venue.

OUGS President Dr Steve Blake rounded off our weekend with a summing-up of these wide-ranging lectures.

Once again, it is unfortunate that some of our lecturers cannot find the time to write up their lectures into these short, but informative articles. I wish to express my gratitude to those who do, and for their cooperation in helping me to prepare their texts for publication. I assure OUGS Members that as Proceedings Editor I will continue to do my best to persuade all our AGM and Symposium speakers to honour us with the not-really-so-onerous task of setting their research words into print, to disseminate their hard-won knowledge in the Earth Sciences to us all.

An issue of the OUGS Proceedings *would not be complete without contributions from OUGS Members. This issue includes four.*

In my first ever geology course at UC Berkeley — way back then — our textbook included only a few paragraphs and diagrams about continental drift and plate tectonics, as an 'interesting but as yet unproven theory'! Now de rigueur, the study of plate tectonics continues to find refinement and further explanation. Dr Françoise Chalot-Prat (CRPG, Lorraine U, Vandoeuvre-les-Nancy, France) and our very own OUGS Elisabeth d'Eyrames provide us with a revealing summary of such refinement, describing and explaining the general westward drift of tectonic plates.

We then return to Spain, to Almería, with Duncan Woodcock — our 'continuing ES student' — to explore the crater-like depression of El Hoyazo, near Nijar, and its garnet-laden sands.

Julian Overnell writes about his thin sections again, this time about dendritic exsolution structures in "coarsely crystalline olivine pyroxenite from Fuerteventura, Canary Islands."

Lastly, we go to Turkey. In the continuing legacy of the OU's founding Professor of Geology, Ian Gass, Alison Ure received an Ian Gass Bursary to study a ring of islets in Kaş Bay, which she is convinced forms evidence for a meteorite crater. Her convincing 'story' makes an exciting read.

Completing this issue, OUGS Reviews Officer Jane Michael has again persuaded publishers to send us books for review. There are 18 for you.

Finally, I once again express my gratitude to all those who help me produce this publication: to our worthy transcribers who toil through the AGM and Symposium lecture recordings (this year: Yvonne Brett, Helen Coombs, Lizzie Davenport, Maggie Deytrikh, Dick Millard, Anne Morton, Isabel O'Brien, Michael Perkins and Susan Pyne); to Don Cameron and Sue Vernon for their continued support and advice; and to our proofreaders Sue Hughes and Isabel O'Brien. And I cannot leave out my wife, Anne, for her continued sympathy when listening to my complaints about the difficulties of page layout!

As always, I wish you happy reading.

— David M. Jones, OUGS Proceedings Editor

Erratum

Eagle-eyed readers of last-year's *POUGS* volume 3 will have spotted that title pages of some of the articles unfortunately have incorrect volume and year information in their 'footers', although page numbers are correct. This is an editorial error, for which I am gravely sorry! All should of course be '*Proceedings of the OUGS 3 2017*'. The digital archive has been corrected, however, and the corrected file has been uploaded to the OUGS Website by Webmaster Stuart Swales.

OUGS AGM 2017 Keynote Lecture

Mass extinctions in the history of life

Dr Luke Mander

School of Environment, Earth and Ecosystems Sciences, The Open University, Walton Hall, Milton Keynes MK7 6AA
Luke.Mander@open.ac.uk, Luke.Mander@gmail.com

Abstract

Life on Earth is extraordinarily diverse. It has been estimated that there are 5.5 million insect species alive today, and this includes 1.5 million species of beetles alone. However, rocks from deep in Earth history show that the world about 560 million years ago contained just a handful of different organisms. Life has therefore expanded in some way from a low-diversity origin to the enormous diversity and complexity that we see today. The fossil record has biases but represents an empirical record of this process. One view of this process is that the Earth has a carrying capacity and that the diversity of life is somehow limited or capped, but an alternative view is that the diversity of life on Earth has no limit. The diversification of life has not been a smooth and steady increase in the number of species through time. Instead, the fossil record shows that the history of life has been punctuated by a series of mass extinctions, and a classic example is the extinction of the dinosaurs at the end of the Cretaceous Period. These mass extinctions demonstrate the resilience of life to major environmental change, and can provide data on how the biosphere may respond to future anthropogenic environmental change.

The diversity of life on Earth

The diversity of Life on Earth has fascinated people since the earliest attempts to describe the natural world. In his treatise *History of Animals*, for example, Aristotle made an attempt to arrange the diversity of animal life into some sort of order. He made sense of the diversity he saw by grouping organisms into categories according the characteristics that they shared: animals with blood versus without blood, animals with legs versus without legs, animals that are wet versus dry, and so on. This produced an arrangement of living things that has been described as a great chain of being, with animals of lower grades successively overlain by higher creatures, and with humans at the top of the pile.

Many centuries later, Carl Linnaeus published S*ystema Naturae*, in which he articulated a view that the diversity of life could be fitted into a nested hierarchy that began with very broad divisions and ended with very fine divisions. For Linnaeus, all life could be first divided into three kingdoms: animals, vegetables and minerals, and this is the origin of the game 'animal, vegetable or mineral?' Each kingdom was divided into classes, which were divided into orders, and these in turn were divided into genera. Each genus was itself divided into species, and Linnaeus provided for the possibility of genera containing just a single species. Genera and species were each given separate names, and this is known as the binomial system of Linnaeus. Our own genus and species is a classic example of this system: *Homo sapiens.*

Systema Naturae was published in various editions from 1735 to 1793. It contained *c.* 10,000 organisms that were described and named using the binomial system of Linnaeus; and this system of nomenclature was so successful that it is still in use today (although in a slightly modified form). If you walk through the countryside of the UK identifying plants and other wildlife, for instance, you will likely be able to spot the pedunculate oak (binomial name *Quercus robur)*, the house sparrow (*Passer domesticus*) or perhaps the oystercatcher (*Haematopus ostralegus*) if you are near the coast.

However, the number of species that are thought to exist on Earth today is far greater than 10,000. There are more than 1.2 million species that are catalogued in a central database, but it is thought that some 86% of existing species on earth and 91% of species in the ocean still await description (Mora *et al.* 2011). This means that there are potentially *c.* 8.7 million species living on the globe today (Mora *et al.* 2011), and in this essay I outline a palaeontological perspective on how this diversity has arisen. I begin with a review of the nature of the fossil record before discussing the processes of diversification and extinction. I will use one particular extinction event — the end-Triassic mass extinction — as a vehicle for exploring issues of extinction risk, and close with some thoughts about how such data from the fossil record can shed light on the current biodiversity crisis.

The nature of the fossil record

It is generally thought that filamentous fossils from the 3.5 billion-year-old Apex Chert in Western Australia represent the first direct evidence for life on Earth (Schopf *et al.* 2017). These fossils are simple, show evidence of cellular structure, and have been tentatively assigned to five taxa (Schopf *et al.* 2017). Their simplicity, and controversy in terms of interpretation, illustrates a general pattern: as one looks backwards in time using the fossil record, the diversity of life decreases compared to the present day, and the types of organisms that are found as fossils become increasingly difficult to interpret in terms of life as we know it today.

For example, fossil reefs from the Pleistocene (*c.* 2.6 million to 11,700 years ago) of the Indonesian archipelago look much the same as reefs today, but the reefs of the Ordovician Period (*c*. 485–444Ma) looked very different indeed, with a variety of now-extinct organisms such as trilobites living along side extinct brachiopod clades (a clade is group of organisms containing all the evolutionary descendants of a common ancestor). The same can be said for the forests growing in tropical latitudes. During the Pleistocene, tropical rainforests probably looked much as they do today: highly diverse ecosystems dominated by angiosperms (flowering plants). However, during the Carboniferous Period (*c.* 359–299Ma) forests growing in the tropics contained no angiosperms, and were formed by giant and now extinct relative of the small horsetail plants that grow today.

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Darwin questions the rocks

How much confidence do palaeontologists have in such glimpses of ancient worlds that are provided by the fossil record? This was a question that preoccupied Charles Darwin, and an entire chapter of *On The Origin of Species* is entitled 'On the Imperfections of the Geological Record'. The chapter is littered with questions and observations that palaeontologists are still actively debating and discussing today, and one passage is worth quoting directly because it neatly summarises the problems palaeontologists face when reconstructing the history of life with fossils "*On the poorness of our Palaeontological collections.*— That our palaeontological collections are very imperfect, is admitted by every one. The remark of that admirable palaeontologist, the late Edward Forbes, should not be forgotten, namely; that numbers of our fossil species are known and named from single and often broken specimens, or from a few specimens collected on some one spot. Only a small portion of the surface of the earth has been geologically explored, and no part with sufficient care, as the important discoveries made in Europe every year prove. No organism wholly soft can be preserved. Shells and bones will decay and disappear when left on the bottom of the sea, where sediment is not accumulating." (Darwin 1859, 632–3).

A rebuttal to Darwin

Darwin's concerns with the fossil content of rocks have not gone away, and they are still subject to active research by palaeontologists. Indeed, his pointed comments gave rise to the discipline of taphonomy, which is concerned with studying the process of how organisms enter the fossil record, and with measuring the quality of the fossil record through time. In truth, and right upfront, Darwin's concerns have not entirely disappeared, but palaeontologists have also spent a considerable amount of time gathering data in rebuttal to Darwin's thoughts about the problems with palaeontological data.

For example, while it is true that many fossil species are named from single or broken specimens, or from a few specimens collected from a single locality, studies of the relationship between assemblages of living molluscs and their recently dead counterparts in nearby sediments highlights that death assemblages retain a strong signal of species' original rank orders (Kidwell 2001). In some cases, because the fossil record is time averaged (fossil assemblages do not represent an instantaneous snapshot of a single day in time) fossil assemblages can preserve evidence of rare species that are often absent from ecological surveys of modern ecosystems (Kidwell 2001). Thus, in certain situations the fossil record can provide a more accurate picture of the Earth's biota than surveys of living ecosystems (Kidwell 2001).

It is also true that a relatively small portion of the surface of the Earth has been geologically explored. The tropics, for example, are extremely difficult to work in geologically because of the dense vegetation cover and high weathering rates in low latitudes. Similarly, regions such as Antarctica and Greenland are currently covered in ice, which also hampers geological exploration. As a consequence, our understanding of the history of life is biased towards certain regions, and it is known that palaeontological data are biased towards North America and Europe simply because of the amount of work that has been undertaken in these regions over time. However, palaeontologists have now collected sufficient volumes of data that they are at least able to quantify the relative importance of geological versus biological controls on the patterns of biotic change that are revealed by the fossil record (Smith and McGowan 2007).

Some of Darwin's views are simply incorrect perhaps as a consequence of the lack of palaeontological work that had been undertaken at the time he was writing *On the Origin of Species*. The spectacular soft-bodied fossils that are present in exceptional fossil biotas such as the Burgess Shale (Gould 1989) clearly demonstrate that his comment "No organism wholly soft can be preserved" (Darwin 1859, 632–3), for example, was overly pessimistic. Nevertheless, even a cursory thought about the preservation potential of an earthworm compared to the shell of a clam living in the ocean will show that the fossil record is biased toward certain organisms, and especially toward those with hard parts that live in regions of the world that are actively accumulating sediment.

The history of life

It is clear, then, that the fossil record is an imperfect archive of the history of life. It is certainly biased, both geographically and taxonomically, but sufficient volumes of palaeontological data have been produced that the quality of the fossil record can at least be quantitatively assessed, and certain biases controlled for when interpreting palaeontological datasets (Benton and Emerson 2007). Additionally, palaeontologists generally think that sampling at quite coarse levels, such as genera or families at the level of stratigraphic stages, can overcome the problem that older fossils are less well represented than younger fossils, because geological processes overwrite the oldest parts of the rock record (Benton and Emerson 2007). In other words, it is thought the history of life as recorded by fossils is not "an illusion brought about by a fossil record that diminishes in quality back in time, so a pattern of static diversity over hundreds of millions of years looks as if it is rising towards the present day as the quality of sampling improves" (Benton and Emerson 2007, 23).

Diversification

Life diversifies as species are added to the global stock of taxa. If the rate of species production exceeds the rate of species loss, then global diversity will rise and diversification will occur. In the coarsest possible sense, the fossil record demonstrates that this has occurred: life has demonstrably expanded from the taxonomically depauperate ecosystems represented by 3.5 billion-year-old rocks in Western Australia (Schopf *et al.* 2017), to the rich and diverse world that contains *c.* 8.7 million species today (Mora *et al.* 2011). The fossil record has also provided data with which to construct models for the boundaries to the process of diversification.

One view is that diversity increases from the origin of life to an equilibrium point. From this perspective, the world is viewed as an island and has a fixed carrying capacity (Sepkoski 1978): a level that marks the limit of global species richness (Benton and Emerson 2007). This viewpoint is attractive because it is rooted in classical ecological experiments in competition where an increase in one population suppresses another population that depends on the same limiting factor (Benton and Emerson 2007). Examples include sunlight in a forest, the availability of nutrients such as nitrogen, and the simple notion that organisms need physical space in which to exist.

Such a view also seems to make intuitive sense: presumably there is indeed a limit to the number of species that can exist on Earth — otherwise diversification would last forever. The notion of physical space as a resource is useful in this context. If a situation were ever reached in which space on Earth became a limiting factor, then presumably ever-smaller organisms would be favoured by natural selection, and perhaps the ultimate limit to diversity might be the availability of the chemicals required for life, such as carbon (Benton and Emerson 2007).

An alternative view is one of continual diversity expansion. In this view the Earth has no limit to its carrying capacity and, perhaps subject to the constraints of physical space, the Earth has not yet reached a diversity limit at any point in the geological past or at the present day. The evolutionary lineages that constitute the Earth's biota have indeed undergone spectacular radiations over the last few hundred million years. The insects for example have ballooned in diversity through the Phanerozoic, and the flowering plants, which are a relatively late addition to the Earth, have diversified rapidly since their evolutionary origin in the Early Cretaceous Period. Of crucial importance in support of the expansionist view of diversification is that major lineages such as these do not appear to have run their course (Benton and Emerson 2007). Instead, their diversification continues apace, and there is nothing to suggest that new species will not evolve and either expand into existing, but currently unoccupied, areas of ecological space, or create new ecological spaces by symbioses and mutualisms.

Extinction

Regardless of which particular view one takes, life has unequivocally diversified and expanded dramatically from the origin of life to the present day. However, this process of diversification has not been a smooth one, and the long-term history of life is not characterised by the smooth and steady addition of taxa to the Earth's biota as a consequence of speciation. Instead, the process of extinction permanently removes taxa from the world; it causes the termination of an evolutionary lineage, either at the species or genus level, or occasionally at higher taxonomic ranks such as the family level. This process represents a means by which the net rate of diversification through time is slowed down.

Extinction is a part of life. The fossil record demonstrates that extinction happens all the time as part of the natural course of things, and it is generally thought that *c.* 99% of all the organisms that have ever existed on Earth are now extinct. Most extinction occurs as part of what is termed 'background extinction'. This is a term used to describe the steady trickle of taxa that leak from the reservoir of extant organisms to the pool of extinct biota with no fuss or drama and with no apparent cause other than simply running out of evolutionary time.

However, there are intervals in Earth history when the rate of extinction was raised considerably, and the diversity of life was substantially reduced. These intervals are known as 'mass extinctions', and they are defined as "any substantial increase in the amount of extinction (lineage termination) suffered by more than one geographically widespread higher taxon during a relatively short interval of geologic time, resulting in an at least temporary decline in their standing diversity" (Sepkoski 1986, 278). Several episodes of elevated extinction in Earth history fit this description and there is a continuum in the magnitude of diversity loss between the largest and smallest extinction events. However, episodes of elevated extinction during the Late Ordovician (*c.* 445 Ma), Late Devonian (*c.* 376 Ma), Late Permian (*c.* 251 Ma), the end-Triassic (*c.* 200 Ma) and end-Cretaceous (*c.* 65 Ma) periods, are noted for their extremely high extinction rates and are collectively termed the 'Big Five' Phanerozoic mass extinctions (Benton 1995).

These mass extinction events are a diverse bunch, and the following information on the magnitude of extinction and the principal organisms lost has been synthesised from the review of Bambach (2006). The Late Ordovician extinction saw 57% extinction of marine invertebrate genera as a whole. During this event the following groups suffered 67% extinction or greater: brachiopods, nautiloid cephalopods, trilobites, crinoids and conodonts.

The Late Devonian extinction saw 35% extinction of marine invertebrate genera as a whole. Sponges, rugose corals, brachiopods, trilobites and placoderms all suffered greater than 65% extinction.

The Late Permian extinction saw the loss of 56% of all marine invertebrate genera. Organisms that suffered greater than 56% extinction include fusilinid foraminifera, rugose corals and brachiopods. Sedentary taxa with massive carbonate skeletons suffered 90% genus extinction.

The end-Triassic event was characterised by 47% extinction among marine invertebrates. Groups suffering more than 67% extinction include sponges, scleractinian corals, brachiopods, nautiloid cephalopods and ammonites.

The end-Cretaceous event is famous for the extinction of the dinosaurs, but marine invertebrate genera suffered 40% extinction. Groups with greater than 60% genus-level extinction include foraminifera, sponges, brachiopods, bivalves and ammonites.

The causes of these extinction events are widely and at times hotly debated. There are two principal geological phenomena that are temporally linked with episodes of mass extinction in the geological record: the eruption of flood basalts and the impact of extraterrestrial bodies. The classic example of this is the end-Cretaceous when a bolide struck the Earth on the Yucatán Peninsula, and the Deccan traps erupted in India. Other examples include the eruption of the Siberian traps during the end-Permian mass extinction, and the eruption of flood basalts in the proto-Atlantic Ocean during the end-Triassic extinction event. Of course, extinction is a biological not a geological phenomenon, and the crucial thing is to establish exactly how the impact of a bolide or the eruption of flood basalts could lead to the death of marine and terrestrial organisms.

This exercise is fraught with difficulty, but the essential point is that these two geological phenomena are thought to create environmental conditions that lead to the death of individual organisms, which eventually escalates to the collapse of ecosystems and the death of all individuals within a species. A typical kill mechanism suggested for bolide impacts is a temporary reduction in the amount of light reaching the Earth, which would disrupt photosynthesis, and the lowering of global temperatures that such light-blocking would produce. For the eruption of large igneous provinces, environmental stresses that are frequently mentioned in the literature include the production of noxious gases such as hydrogen sulfide and sulfur dioxide, and the release of carbon dioxide to the atmosphere together with the corresponding rise in global temperatures.

The end-Triassic mass extinction: a natural extinction experiment

One of the most compelling things about studying mass extinctions is that they offer an opportunity to examine the intricate relationship between the evolution of Earth's physical environment and the evolution of life. Although boundary conditions, such as the configuration of the Earth's tectonic plates and the composition of Earth's biota, were rather different to today, the end-Triassic is a particularly interesting interval of time in the context of the current anthropogenic climate and biodiversity crises. This is because the end-Triassic coincided with the opening of the Atlantic Ocean, a tectonic process that resulted in the eruption of huge volumes of flood basalts in the Central Atlantic Magmatic Province (CAMP). The eruption of the CAMP basalts is thought to have produced a fourfold rise in atmospheric CO_2 as a result of volcanic degassing (McElwain *et al.* 1999), and this interval of Earth is history viewed as one of many such periods that can provide insight into biodiversity and ecology in a greenhouse world.

The fossil record of both plants and animals during the end-Triassic extinction event is rich and informative. Researchers have spent a great deal of time trawling through published palaeontological studies of the distribution of fossils in single rock successions and pooling the results into large databases and compendia of the stratigraphic ranges of fossils (e.g. Benton 1995). Such global databases provide a broad perspective on biotic events at the end-Triassic and highlight the pattern of extinction among different groups of organisms at this time.

The Ceratitina, a group of ammonites, and the conodonts suffered total extinction during the end-Triassic. Calcareous sponges were almost eliminated at this time with just two families surviving, five bivalve families suffered extinction, and spiriferid and terebratulid brachiopods suffered more than 67% genus-level extinction during the end-Triassic (Bambach 2006). Reefs and reef-building organisms were profoundly disturbed during this extinction (Kiessling *et al.* 2007), leading to a pronounced decline in coral reefs in the early part of the Jurassic Period. Certain groups appear to have survived the end-Triassic pretty well. Among echinoderms, all 34 families of echinoid present in the Late Triassic range into the Jurassic and just one family of crinoids, the Somphocrinidae, suffered extinction at this time. Similarly, all 35 gastropod families that are present in the Late Triassic range into the Early Jurassic (Hallam 2002). Eleven reptile families suffered extinction in the Late Triassic (Benton 1995), but among higher plant taxa only the Peltaspermaceae, a family of seed-ferns, disappeared during the end-Triassic extinction (McElwain *et al.* 2007).

Such palaeontological data serve to outline the patterns of biotic upheaval associated with the end-Triassic mass extinction — and certainly this was a dramatic event in the history life that represents a major reorganisation of the Earth's biota — but they also allow the factors that increase extinction risk and promote survivorship to be evaluated. Such factors are of crucial importance in the study of mass extinctions because they provide pieces of information that may be of practical significance to conservation biologists and other applied scientists who seek empirical data on how species respond to climatic change that is beyond the scope of neontological data.

Such data have suggested that factors such as abundance, mode of reproduction, body size, geographic range at the species level, and species richness, are all correlated with extinction risk in today's biota (Jablonski 2005). However, these same traits turn out to be poor predictors of survivorship during mass extinctions in Earth history such as the end-Triassic event (Jablonski 2005). Instead, at least for animal taxa, and marine invertebrates in particular, the strongest predictor of survivorship during mass extinctions is broad geographic range at the clade level: an emergent property that is independent of the geographic ranges of the constituent species (Jablonski 2005). This is crucial, because it demonstrates that the fossil record can tell us something about the way biodiversity is regulated over evolutionary timescales that is not apparent from data gathered from living organisms alone.

Concluding remarks: the sixth mass extinction and the fossil record

In this essay I began by outlining how diversity is a first-order property of the Earth, and that we as humans have been fascinated by it for centuries. Living creatures are certainly enormously and impressively diverse, but the fossil record harbours a vast store of ancient life forms that are now extinct. This fossil record is, as Darwin said, somewhat imperfect, but it is our only physical evidence of the history of life on Earth, and palaeontologists are now at least confident that biases in the record can be quantified and acknowledged.

I also discussed how the fossil record has been used to think about how life has diversified from a single common ancestor to the dazzling array of species alive today. For some, diversification is capped to some equilibrium level, but for others, the rampant speciation of groups like the flowering plants, which shows no sign of slowing down, is evidence that there is essentially no limit to the potential diversity of life on Earth. I then outlined how the process of extinction has periodically been accelerated to such a high degree that the biosphere has been decimated by five large mass extinctions during Phanerozoic time.

For me, the value of studying ancient extinction events does not really lie in the demonstration that that a particular group of group of organisms went extinct at some particular time in Earth history. Instead, the dynamics of extinction events, which I discussed here in terms of organismal and clade-level traits that affect extinction risk and survivorship, shed light on aspects of biospheric organisation that are simply not apparent from the world as we see it today. Given that we may be approaching a sixth mass extinction on Earth, I would argue that only data from the fossil record has the potential to provide meaningful data on what the biosphere can expect in the centuries and millennia to come.

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Book review

Maddox, Brenda 2017 *Reading the Rocks: How Victorian Geologists Discovered the Secret of Life*. London and New York: Bloomsbury (hardback ISBN 978-1-4088-7958-0; also available in TPB ISBN 978-1-4088-7960-3 and ePub ISBN 978-1-4088-7961-0; 253pp; hardback £20.00)

Brenda Maddox is a professional journalist and biographer, with a dozen other biographical books to her name. And it is with a biographical approach that she writes about Victorian geologists in their quest to unravel the facts of and establish the science of geology and palaeontology.

In 19 solid chapters she chronicles the rise of her subject matter from the inquisitive churchmen and assorted amateur natural historians to end in chapter 19, Then and Now, with a typical point: "One could weep for all that Victorian geologists did not know that is common knowledge today. Darwin, who died in 1882, never knew of genes or chromosomes …" And ending with the conclusion that if Richard Fortey explained to Charles Lyell that Vesuvius is the consequence of the African plate plunging beneath the geology of Italy as part of another plate, a European plate, Lyell's reaction would have been, "At the very least, a new edition of *Principles [of Geology]*…"

It is this spirit of never-ending discovery that Maddox describes and explores. She seems to include everyone who ever mattered in 19th-century British, American and European geology, thus showing the international nature of the quest.

She begins with the crucial fact that, "By 1837, when the eighteen-year-old Victoria ascended the throne, the new science of geology had shown the planet's hidden past extending back beyond human imagination, certainly beyond human existence." This fact, in the common TV vernacular of today, was clearly 'paradigm shifting'. There was no turning back.

Maddox did a massive amount of reading and research to write this book, which shows in her eleven-page 'Select Bibliography' — which, pleasingly, even includes the entry: "*Open University, Geological Society Journal* Symposium Edition, 2008, Volume 29 (2)" [the one at U London, Egham]!

While there is nothing especially 'new' about Maddox's subject matter, her clear and readable style — that of an extremely competent journalist — races right along.

Reading her book 'reminded' me of a lot of things, put many things into new perspectives, and pulled together a lot of fragments about how our subject developed. She has done all of us a great service in putting together such a vast topic into a sweeping history that I recommend we can all read with profit.

So settle into a not too comfortable armchair with this book and prepare to turn a lot of pages before placing your bookmark into it and 'saving' something for later. [I read this book in just three sittings.]

A so-called 'popular science book', Maddox adheres to scholarly practice and includes 18 pages of Notes, citing sources. And as to the 'who' — to apply the classic journalist's 5-Ws and How? — there are two interspersed sections of plates (the book kind) with portraits of many of the principal stars of the story.

— Dr David M. Jones, OUGS Proceedings Editor

Book review

White, Mark J. 2017 *William Boyd Dawkins and the Victorian Science of Cave Hunting (Three Men in a Cavern)*. Barnsley: Pen and Sword Books (ISBN 978-1-47382-335-8; 302pp; hardback £25 / $39.95)

I found this an absolutely fascinating book. Mark White gives a comprehensive account of the academic life and geological activities of one of the most intriguing characters of 19th century Britain, as well as an insight into the origins of Manchester Museum.

The book is wide ranging in content, dealing with the beginnings of geological study in the north of England, the exploits of early archaeologists, the 'Cave Hunters', vicious academic disputes, some bizarre ideas in palaeontology and climate change, and some very dodgy dealings. It is lavishly illustrated with photos of the protagonists and artefacts, and copies of Dawkins' notebook sketches of excavations.

Son of a Welsh vicar, Dawkins had a good education at Rossall and Oxford and 'took up' archaeology and cave hunting with vigour, and then went on to be engaged in geology. He excavated and dug in Cheddar and Creswell and many other caves.

He worked for the BGS for five years and then got the post of Curator at Owen's College in Manchester, the future Manchester Museum, rapidly progressing to a professorship.

Mark White details Dawkins' excavations, his academic arguments and disputes, which throw much light on the prevailing academic atmosphere in the 19th century.

The book is so wide ranging that it's not possible to mention all of its richness, but a particular chapter on Dawkins' explanation of why in one cave there could be deposits of lions, hyenas and hippopotamuses along with those of mammoths and musk oxen was that there was an annual seasonal migration from north to south and back of the creatures from the different 'Geo-climactic Groupings' in the Pleistocene. He was unable to comprehend James Geikie's ideas of repeated glaciations and they were in bitter dispute for many years. [Editor's note: see 'Nineteenth-century battles over bones and ice: Geikie versus Dawkins' by Anne O'Connor, *OUGSJ* **29** (2), 2008, 66–9]

The book also gives the history of two more contemporaneous controversies: did Dawkins hoax the scientific community by planting evidence in Creswell Cave, e.g. a *Machairodus* tooth (sabre toothed cat) from elsewhere and then arguing that the sand adhering to it had improbably changed colour, or didn't he? After an exchange of letters and publication of papers and press articles the matter came to a head in 1880 at a very acrimonious and protracted meeting of the Manchester Geological Society at which many accusations were made and refuted. There was also the matter of an engraved bone 'found' at Creswell, which bore a remarkable similarity to one found at Sherborne (later found to be a forgery): again much controversy and argument ensued in the scientific press and local newspapers. Nothing was settled. The arguments and records left much to be desired! Echoes of the Piltdown hoax resonate.

My own interest is a particular one: I volunteered for ten years at the Manchester Museum cataloguing fossils and am personally acquainted with some of Dawkins' specimens. One remark that I vividly remember is of one volunteer asking "How many zeds in grizzly, Alan?" They were re-boxing the bones from Windy Knoll cave!

If you have an interest in early geology or archaeology, at £25, this book is a bargain.

—Mary Howie, BA (Hons) Open, sometime museum volunteer in Manchester and Buxton

OUGS AGM 2017 Geoff Brown Memorial Lecture

Mt Erebus, Ross Island, Antarctica — an active volcano

Dr Clive Oppenheimer

[delivered 13 May 2017 at the OUGS AGM in Milton Keynes]

[Unfortunately, Dr Clive Oppenheimer was unable to write up his lecture as an article for the OUGS Proceedings*. His lecture was recorded, but when he replied to our contact about his article he declined a transcription, so we sent him the recording itself. As there is no transcription of the recording, and because there are sections that would require resolutions to queries, it has not been possible to publish a readable transcription.*
Unfortunately, we have no abstract of Dr Oppenheimer's lecture either.
For those interested, there is a brief summary of this lecture, including a few photographs, in the Severnside Branch Newsletter Sabrina Times *(July 2017, 8–9; author unidentified). — Ed.]*

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Book review

Wesson, Robert L. 2017 *Darwin's First Theory – Exploring Darwin's Quest to find a Theory of the Earth*. New York: Pegasus Books (ISBN 978-1-68177-316-2); digital copy, 457pp; hardback £23.33 [quoted by Amazon on 28/06/2017])

I read about this book in *Nature* and realised that I knew nothing of Darwin's interest in Geology. Our OUGS Archivist was only able to obtain a digital copy from the Canadian publishers, so this has been an interesting experience — reading an e-book where the illustrations are in separate files. The hardback version is available through on-line bookstores and I quote the price advertised by Amazon.

Most of us are aware of Darwin's trip on HMS *Beagle*, 1831–1836, when he noted the diversity in the creatures that he encountered, and his later work on barnacles, which resulted in the controversial *Origin of Species*. But this book picks out of his diary the observations and thoughts that Darwin had on the physical world that he travelled through. The book explains how Darwin developed his theories of coastal elevation and ocean basin subsidence, and of the creation of coral reefs, and illustrates Darwin's adventures through a comparable journey by the author.

We are told that before Darwin's departure he had an instructive trip through North Wales with Adam Sedgwick, where he developed his skills of rock identification and map-making, and also learned basic geological theories. As a philosophical thinker he corresponded with some of the members of the newly formed Geological Society [of London], including Charles Lyell, author of the first volume of the recently published *Principles of Geology.*

This period in the history of 'Sciences' was one of dispute as new ways of thinking, based on facts and logic, were coming into conflict with faith and religious dogma. This book describes such a conflict and how it shaped Darwin's thinking. It contains a brief history of early geologic disputes and illustrates how scientific theory and methods developed in this often multi-disciplinary field.

The story is presented in two parts.

Part 1: 'Darwin in the Field', where we follow him through the diaries he kept during the voyage of HMS *Beagle* with Robert FitzRoy, in which they were completing a British Admiralty project to map the coastlines of South America, New Zealand and Australia. Darwin had been invited on the voyage by Fitzroy to act as geologist and he made many excursions from the ship to observe and collect examples of the flora, fauna and geology of the regions they passed by. It also includes their account of the 1834 earthquake and tsunami that occurred when the *Beagle* was in Chile.

Part 2: 'Darwin Theorising', describes the construction of Darwin's theories and their presentation at the Geological Society and the writing of his report of the voyage from a geological viewpoint. The retelling is interspersed with a record of Wesson's own journey to revisit the sites Darwin explored and to take part in a new investigation of the record of tsunamis left in the sediments that they deposited.

This book is written for a general audience with some scientific background. It is written in an easily readable style with explanations of scientific terms and geological processes with diagrams where necessary. There is an index, a good bibliography, and extensive and detailed notes at the end, although they are not referenced in the text. There are numerous photographs, but my digital version is not a good indication of their quality or appropriateness, as they are in a separate file and not referenced in the text.

I have enjoyed reading this book and it has added to my knowledge of Charles Darwin and his work, and of the scientific world that he worked in. The book also includes details of current scientific work in Darwin's field of interest and shows that his observations are still relevant today.

— Averil Leaver, BSc Hons Geoscience (Open)

Book Review

Leeder, Mike, and Lawlor, Joy 2017 GeoBritannica: Geological landscapes and the British peoples. Edinburgh: Dunedin (ISBN hardback 978-1-78046-0604, ePub 978-1-78046-5678, Kindle 978-1-78046-5685; 281pp; hardback £24.99 (full price); if you order via Dunedin's website a discount code is available)

This is not a geology text-book, it is a delightful read for geologists, artists and everyone else to enrich their appreciation of how the geology below our feet has shaped our perception of Britain; I liked it so much that when only part-way through I bought one as a present for a friend.

The book is divided into 34 chapters, which are grouped by theme into seven parts. Each chapter opens with at least one quotation: some are written by scientists, some by poets and some by those who can be considered both. By far the largest part is 'Part 7 GeoRegions', which contains almost half the book and includes 18 chapters focussing on different regions of Britain.

The writing was generally very accessible; the only term that stumped me was 'mounded pingos'. My brain tried to fill in the blank by creating an image in my mind's eye of a pile of animated penguins (*Pingus*), but I now know it is a periglacial feature. One small negative is that the book is called 'GeoBritannica', and it focuses on England, Wales and Scotland, but instead of referring to 'Britain', or even to 'Britannica, the authors use 'the Island'. This is not a way of referring to Britain that sits naturally with me; I think I understand why they did this as the opening quotation is by James Hutton, "…the Little Space of this our Island", but this usage *slightly* irritated me all the way through the book.

Early on in the book the authors talk about some of the local terms for geological features and the one that is still making me smile as I write this is that faults were known by Lothian miners in 1672 as 'trouble'.

The landscape around us creates a sense of place even if we do not consciously notice it; the shape of the horizon, the colour of the building materials and the vegetation come together to create a pattern we feel in our hearts as home, and if people are displaced they will often resettle in a similar landscape where possible. The underlying geology and the landscape above it inspire artists, sculptors, architects, poets, writers and scientists from Stone Age religious sites to modern multi-media immersive art where the location is part of the work. When discussing the Romantics the authors quote Samuel Palmer, "The search for a spiritual meaning in nature is a recurring theme in British Art" (page 151), and have a poetic turn of phrase themselves with the caption to a flint axe (Fig. 7.13) reading, "…It was at least half a million years since the implement was last held snug in the warm grip of a hominid hand."

— Helen Coombs, BSc Hons (Geosciences)

OUGS Symposium, Edinburgh 2017: A Festival of Geodiversity

Base metal to gold: mineral deposits and the evolution of the Southern Uplands-Longford-Down Terrane, southern Scotland

Simon Cuthbert

School of Science
University of the West of Scotland
Paisley PA1 2BE

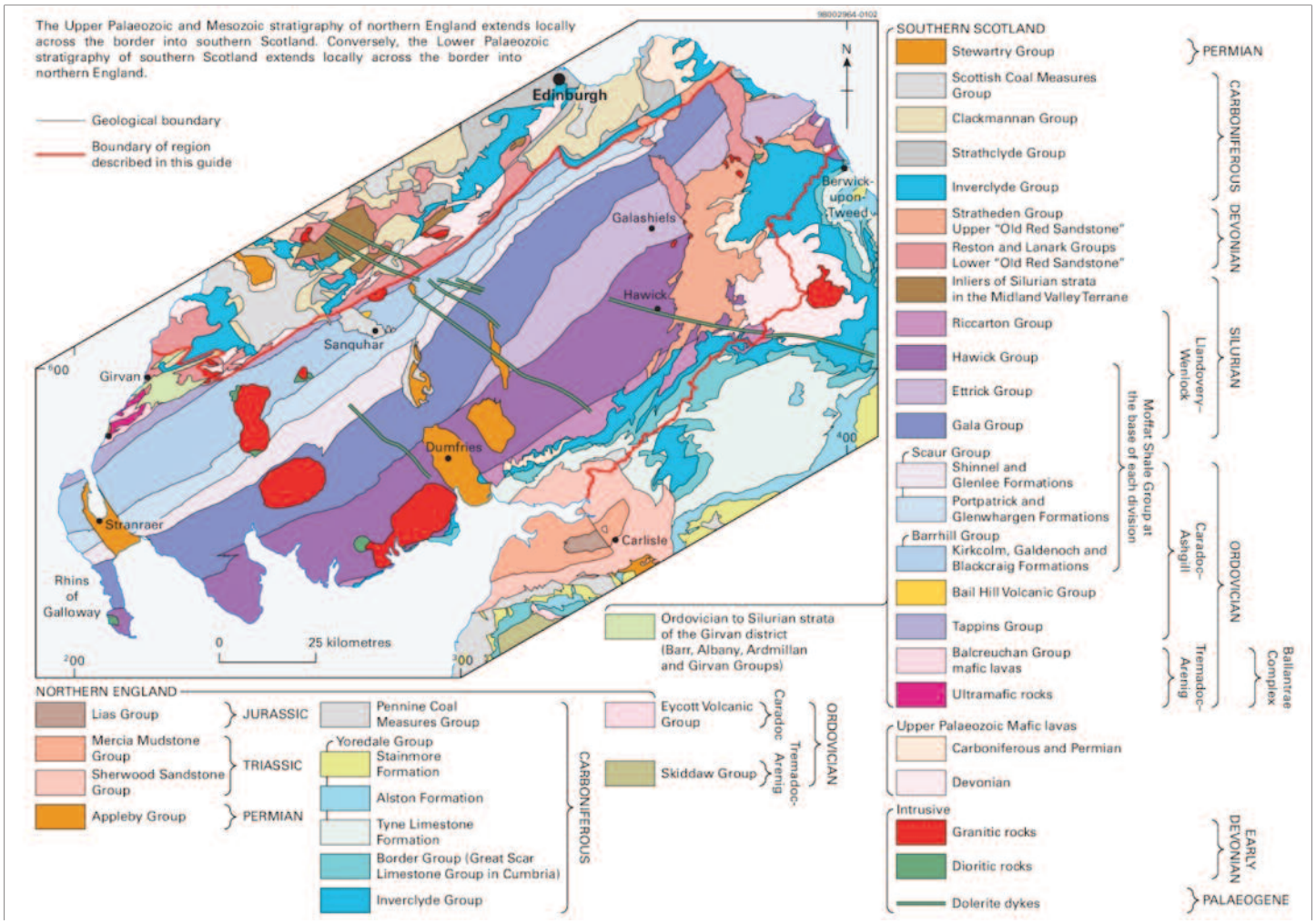
contact: simon.cuthbert@uws.ac.uk

Introduction

The Southern Upland hills make an emphatic geographical statement, almost spanning Scotland from the North Sea to the North Channel, from the Lammermuir and Moorfoot Hills in the east to the mountains of Galloway in the west. A sparsely populated, dissected plateau, these hills separate the urban regions of northern England from central Scotland. Their southern rampart formed a political border for many centuries where cultures and ambitions collided, but its geology marks a much deeper and older division where continents themselves have collided.

The hills rise wherever the product of this collision — the Caledonian Orogen — emerges through its cover of Late Palaeozoic sediments; and their junction is the epoch-making unconformity identified by James Hutton at Siccar Point on the North Sea coast. The dominant rock is greywacke, which many may regard as a singularly uninspiring material, lacking the glamour of the schists and gneisses of the Scottish Highlands rendering the Southern Uplands a bit of a 'Cinderella' as a geological attraction. Yet these rocks have a fascinating story to tell and in among them are mineral riches that have yielded enough to crown kings — enough, indeed, to earn the title 'God's Treasure House on Earth'. The area has seen many 19th- and 20th-century geological heroes cut their teeth in unravelling its geological

*Figure. 1 Geological map of the Southern Uplands of Scotland and adjacent areas (BGS image catalogue number P912313) (http://earthwise.bgs.ac.uk/index.php?title=File:P912313.jpg&filetimestamp=20150726172029&).**



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** The Editor wishes to apologise for some images in this article being of lower quality than usual — there was insufficient time for the author to obtain higher-resolution figures.*

(Charles Lapworth) complications, including Charles Lapworth, Ben Peach and John Horne. And thanks to painstaking work by the British Geological Survey over the last few decades its general geology is now well known.

In this article I summarise the current state of geological knowledge about the Southern Uplands through the lens of the mineral explorer showing the contribution of each episode of its geological developments to its enrichment in base metals and gold. Perhaps there are still riches to be won; who knows? But I hope to show that the Southern Uplands of Scotland is a great place to learn about mineral resources, and much else besides.

Ore formation

The formation of a metal ore deposit requires some special geological circumstances to come together; a primary source of metals; a chemical and physical process to liberate, carry and precipitate them; and conduits to transport the metals (dissolved in hot water, vapour or magma) and emplace them in an ore body. Liberation of the metals from their sources often requires a medium enriched in sulphur or chlorine. Through its long history each part of the geological picture of the Southern Uplands contributed structures, metal sources and fluids to build the mineral resources of this region.

Ordovician–Silurian accretionary prism and foreland basin

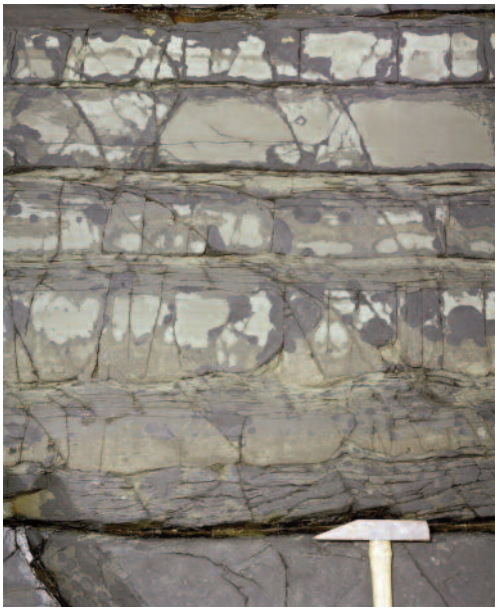
The bedrock geology of the Southern Uplands is distinctive and different from the rest of Scotland (Fig. 1, *previous page*). It is dominated by Ordovician and Silurian sedimentary and volcanic rocks typical of the deep oceans and fore-arc environments of destructive plate margins. These rocks extend across into Co. Down in Northern Ireland and Co. Longford in the Republic of Ireland and are, therefore, called the Southern Uplands-Longford-Down Complex (SULDC). To their north they are bounded by the Southern Upland Fault, which transects the whole of the British Isles from Dunbar to Galway Bay via Girvan and separates the Lower Palaeozoic Geology of the Southern Uplands from the Midland Valley graben to its north. The Southern Uplands Fault separates the SULDC from the Midland Valley graben system, whose outcrop is now dominated by Devonian, Carboniferous and Permian sedimentary rocks, volcanics and mafic intrusions. However, inliers of older rocks that emerge through these Late Palaeozoic strata indicate the presence of a mid-Ordovician-to-Silurian magmatic arc and intra-arc sedimentary basins. These were probably formed on a basement of the Ballantrae Ophiolite and an older metamorphic, continental basement. North of the Midland Valley arc block is the southern and central Highlands Grampian block. These two earlier blocks collided in the Middle Ordovician, creating a mountain range that shed debris into the SULDC and made a significant contribution to its construction.

In south-east Scotland the SULDC is buried by Late Silurian to Permian strata, which were submerged in turn by the Solway Firth in the west. These younger rocks obscure a major, deep-seated tectonic structure — the Iapetus Suture — which marks the plane of collision between the ancient continents of Laurentia to the north and the Avalonia fragment (England, Wales and central and Southern Ireland) of Gondwana to the south. This enigmatic junction marks the location of the former Iapetus ocean basin, thousands of kilometres wide at its greatest extent. This geological conjunction of North America and Europe — a suture from the Solway Firth to Berwick upon Tweed closely follows the English-Scottish border for much of its length.

In detail, the SULDC rocks are dominated by tough, mud-rich ('greywacke') sandstones. Individual strata often become finer grained upwards and are invariably capped by a thin muddy interval (Fig. 2). The tops of these graded strata frequently show signs of erosion by powerful currents that have sculpted swarms of scours into the mud, which are now seen in the negative image as flute marks cast on the base of the overlying sand or gravel. These features signify an origin of each bed as a submarine turbidity flow that likely started in shallow water, then flowed into deep water, hugging the ocean floor, and perhaps travelling hundreds of kilometres before settling out. This sedimentary motif occurred thousands of times to build a pile of strata many kilometres thick. Frequently, a flow lies on a distinctive unit of black, red or green shale and chert, rich in graptolites (e. g. the Moffat Shale Group), often resting on basaltic pillow lavas and other submarine volcanics (e. g. the Crawford Group). These features formed part of the abyssal ocean floor; they must have come into proximity with eroding felsic continental or arc crust in order to have accumulated a thick pile of sandstones on top of them and they exhibit much evidence of derivation from a magmatic arc.

A thrust fault — a complex zone of imbrication that separates the shales and volcanics from an underlying sequence of younger greywackes in the footwall — marks the base of the Moffat Shale and Crawford Groups. These thrust-bounded basement-cover packages of thrust nappes called 'tectonostratigraphic tracts' repeated several times. The Moffat Shale flooring each tract is slightly younger than that at the base of the tract above it. The whole stack has been tilted to dip steeply northward, making SULDC rocks oldest in the north and youngest in the south. But, paradoxically, within each tract most of the strata young northward (with local reversals due to folding) (Fig. 3, *opposite*).

Figure 2 Typical sequence of greywacke turbidite strata from the Southern Uplands — Silurian strata at Port Logan. Note the gradation from a massive, sharp-based sandstone to a flaggy, fine-grained top. (BGS image catalogue number P008471) (http://earthwise.bgs.ac.uk/inderx.php/Depositional_environments,_Ordovician_and_Silurian,_Southern_Uplands).



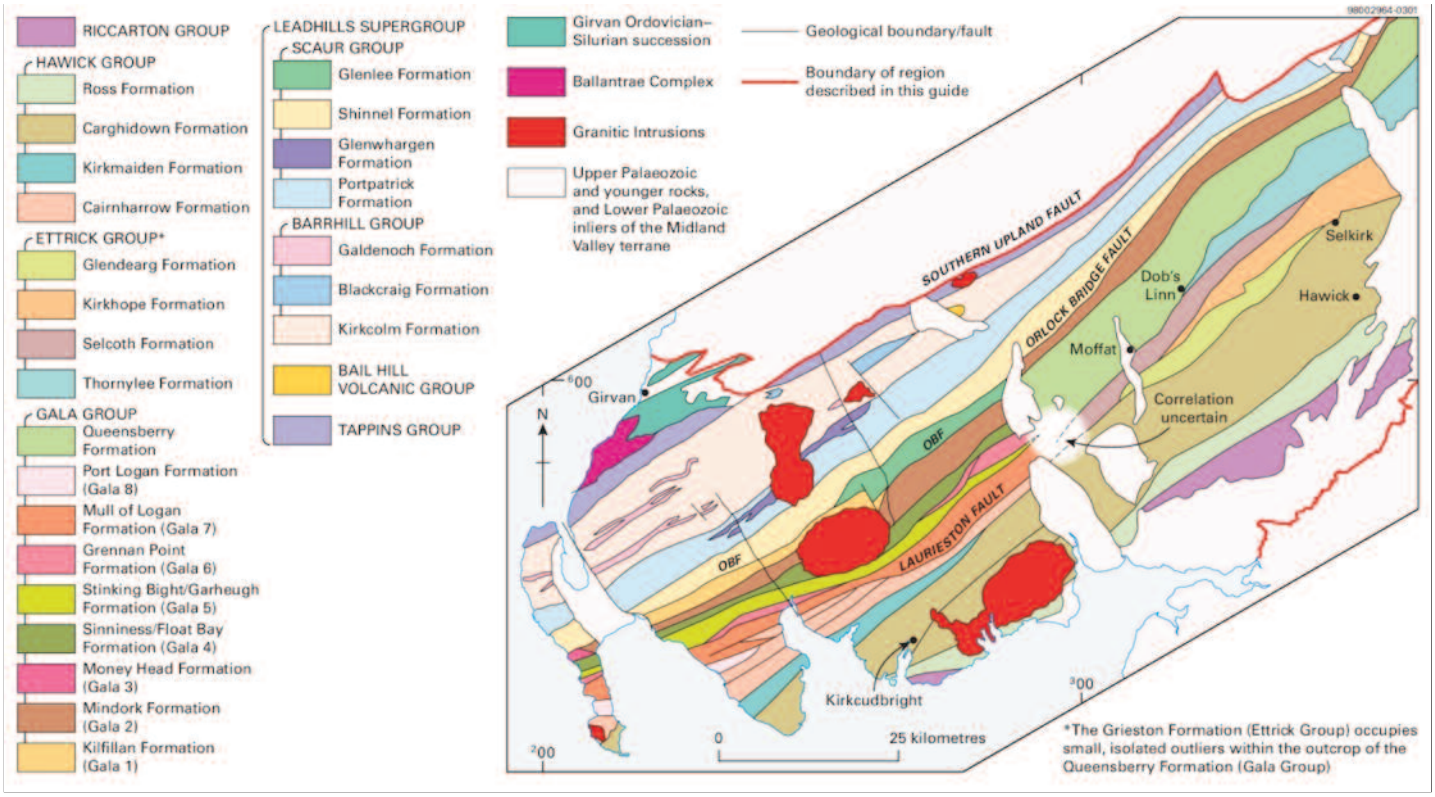


Figure 3 Tectonostratigraphic map of the principal Ordovician and Silurian structural tracts of the Southern Uplands Terrane (BGS image catalogue number P912325) (http://earthwise.bgs.ac.uk/index.php?title=File:P912325.jpg&filetimestamp=20150726172038&).

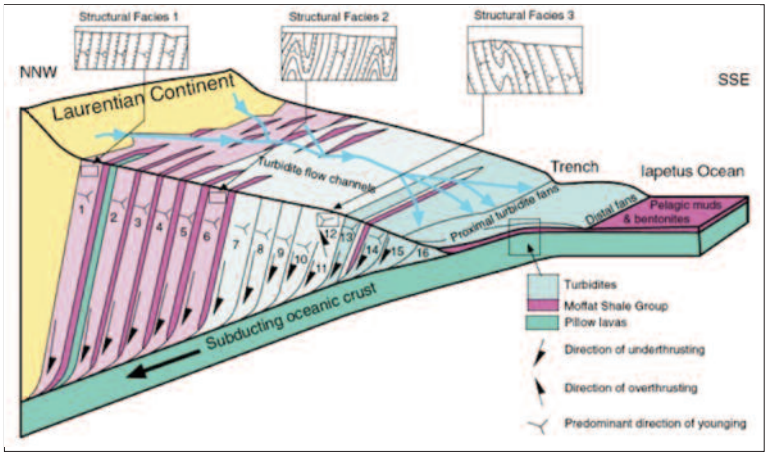
This pattern of stacked slices separated by thrust faults is the result of forward propagation of a thrust system in the fore-arc of a subduction zone (Fig. 4). Here, the ocean trench marks the trace of the plate-boundary thrust fault along which the subducting lower oceanic lithosphere descends into the mantle. Sediment eroded from the adjacent magmatic arc on the upper plate fills the trench with turbidity flow material that comes to rest on the subducting plate surface, which is underlain by submarine volcanics and a cover of muddy pelagic sediments. As the subducting plate continues to move into the subduction zone it attempts to carry its new load of turbidites with it, but this is prevented by the 'back-stop' of the inner trench wall. The shear forces developing at the base of the sediment pile cause it to fail along the weakest layer, the pelagic muds, so the subduction zone thrust fault propagates forward under the turbidites, eventually ramping up through the sediment and breaking the surface at the toe of the sediment pile.

The subducting plate is then free to continue its slide. Sediment continues to flow off the arc and for a while the ocean plate drags under the floor thrust until it jams in the mouth of the subduction zone. The floor thrust breaks forward along the pelagic muds again and detaches another slice from the ocean floor. This process is repeated again and again as floor thrust jacks up the pile of thrust nappes, inserting wedges of rock under the floor and steepens the whole edifice to dip towards the arc. Sometimes the floor thrust breaks down into the volcanic crust of the ocean floor so that slices of pillow basalt are intercalated with the pelagic muds. The fore-arc region of the subduction zone develops a wedge of turbiditic sediments with pelagic muds and pillow lavas sandwiched between them, forming a wedge of detached slices of trench fill. The whole edifice is an 'accretionary prism'. In the SUDLC the Moffat Shales are the pelagic sediments and the Crawford Group the ocean-floor volcanics.

Most rocks of the SULDC, especially the pelitic types, show some foliation, and many of the shales are slate-like. These rocks are metamorphic, showing up in the crystallinity of the clays. The metamorphic facies is mainly prehnite-pumpellyite or lower greenschist. The structurally higher parts of accretionary prisms are a combination of burial load, expulsion of sediment water, deformation and mild heating due to tectonic burial resulting in low-grade metamorphism. At deeper levels metamorphic grades in the base of the accretionary prism can be much higher. The situation is complicated by numerous local igneous intrusions that thermally affect their surroundings.

The SULDC accretionary prism shares many characteristics with other terrains around the world that host economic ore deposits, especially gold. These are sometimes called 'greywacke hosted', 'slate-belt hosted' or 'lode-gold' deposits and today are

Figure 4 Schematic block diagram of the Southern Uplands accretionary complex showing how successive thrust nappes (tectonostratigraphic tracts) are stacked in the fore-arc of a subduction zone above the descending oceanic crust (modified after Chew and Strachan 2014, fig. 15).



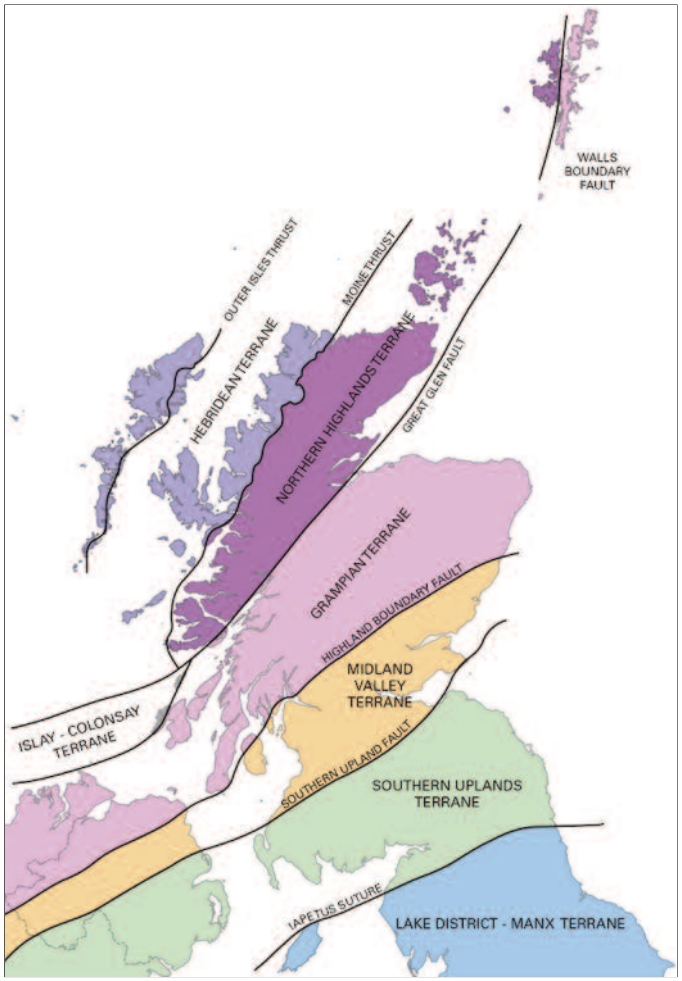


Figure 5 Terrane map of northern Britain (BGS image catalogue number P785801) (http://earthwise.bgs.ac.uk/index.php?title=File:P785801.jpg&filetimestamp=20140610161352&).

generally classed as 'orogenic gold deposits'. A few features of these terrains, including the Southern Uplands and its Irish extension, could have contributed to the concentration of gold and other metals.

First, as the rocks derive from two metal-enriched sources they might have been preferentially enriched from the magmatic arc greywackes and a mid-ocean ridge with metal-rich hydrothermal vent systems where pillow lavas and pelagic muds formed. Second, the Moffat Shales are rich in sulphide (mainly pyrite), providing a source of sulphur that could have aided in mobilising metals. Moffat Shales were also the detachment horizon for the major thrust faults, which that could have provided pathways for the transport of metal-rich fluids and fracture voids for the formation of ore veins. Folds associated with thrusting could have formed the 'saddle reef' structures that often host gold-bearing ore veins (although none have yet been described). Sediment pile dewatering along with water released by mineral reactions associated with metamorphism that could have provided the fluids necessary to mobilise metals and precipitate them in fractures.

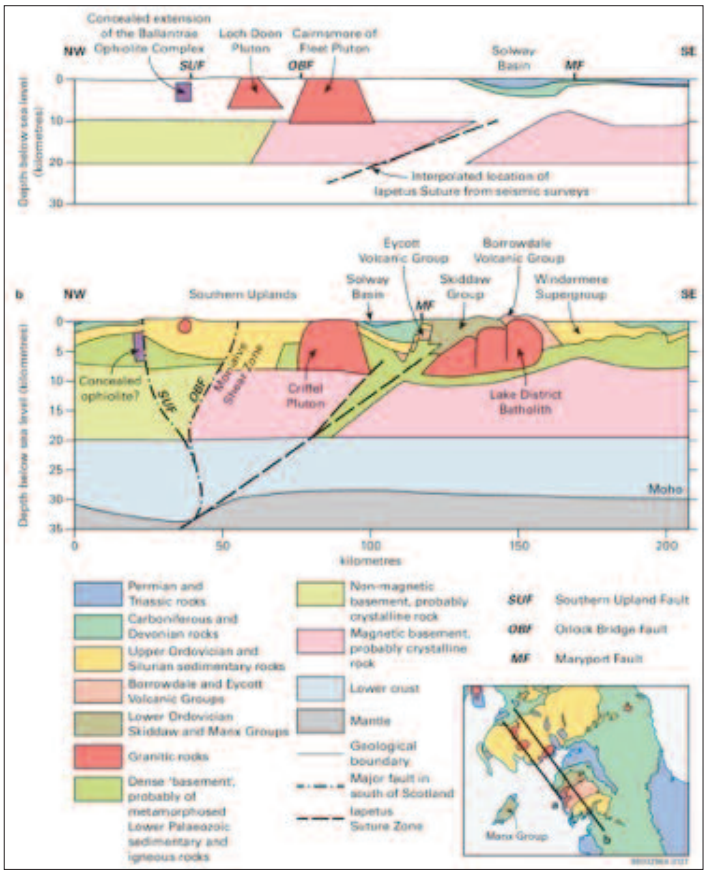
Collision

The Iapetus Ocean closure resulted from the collision of a continental fragment that had drifted from the south. It originated on the northern margins of Amazonia and West Africa (both part of the Gondwana supercontinent). This terrane underlies northern England, the Isle of Man and southern Ireland and is named the Lakesman-Leinster Terrane (LLT) (Fig. 5). The LLT is part of a group of magmatic arcs that included 'eastern Avalonia', and the whole assemblage is sometimes referred to as 'Avalonian' in the literature on the Southern Uplands; it includes the familiar Borrowdale Volcanics and the Skiddaw black slates of the Lake District.

Signs of the approaching collision are first seen in the southernmost SULDC. Here stratigraphic evidence shows that the subduction rate slowed in the late Silurian, possibly because the LLT margin was entering the subduction zone. It has been suggested that the youngest tracts of the SULDC are not strictly a fore-arc accretionary prism but formed in a foreland fold-and-thrust belt as the LLT impinged on the subduction zone. The deformation intensity changes in the southernmost tracts, consistent with the buoyant mass of the approaching Avalonian continental crust jamming up the subduction zone. Geophysical evidence suggests that the SULDC was thrust south over crystalline crust similar to the 'Avalonian' basement of northern England along with its cover of Skiddaw Slate (Fig. 6). Their contact here has been described as 'soft collision' and 'docking', which reflects the limited structural effects of the collision.

Effects of the collision north of the SULDC are sediments of the more proximal fore-arc (preserved near Girvan), showing a simultaneous transition from marine to terrestrial environments. Shortly afterwards, the SULDC was thrust northward over the Midland Valley arc complex, putting the Midland-Valley-type crust below the northern half of the SULDC. The present proximity of the accretionary prism to the Midland Valley volcanic

Figure 6 Crustal cross-sections through the Scottish Southern Uplands and English Lake District based on geophysical data (BGS image catalogue number P912318) (http://earthwise.bgs.ac.uk/index.php?title=File:P912318.jpg&filetimestamp=20150726172034&).



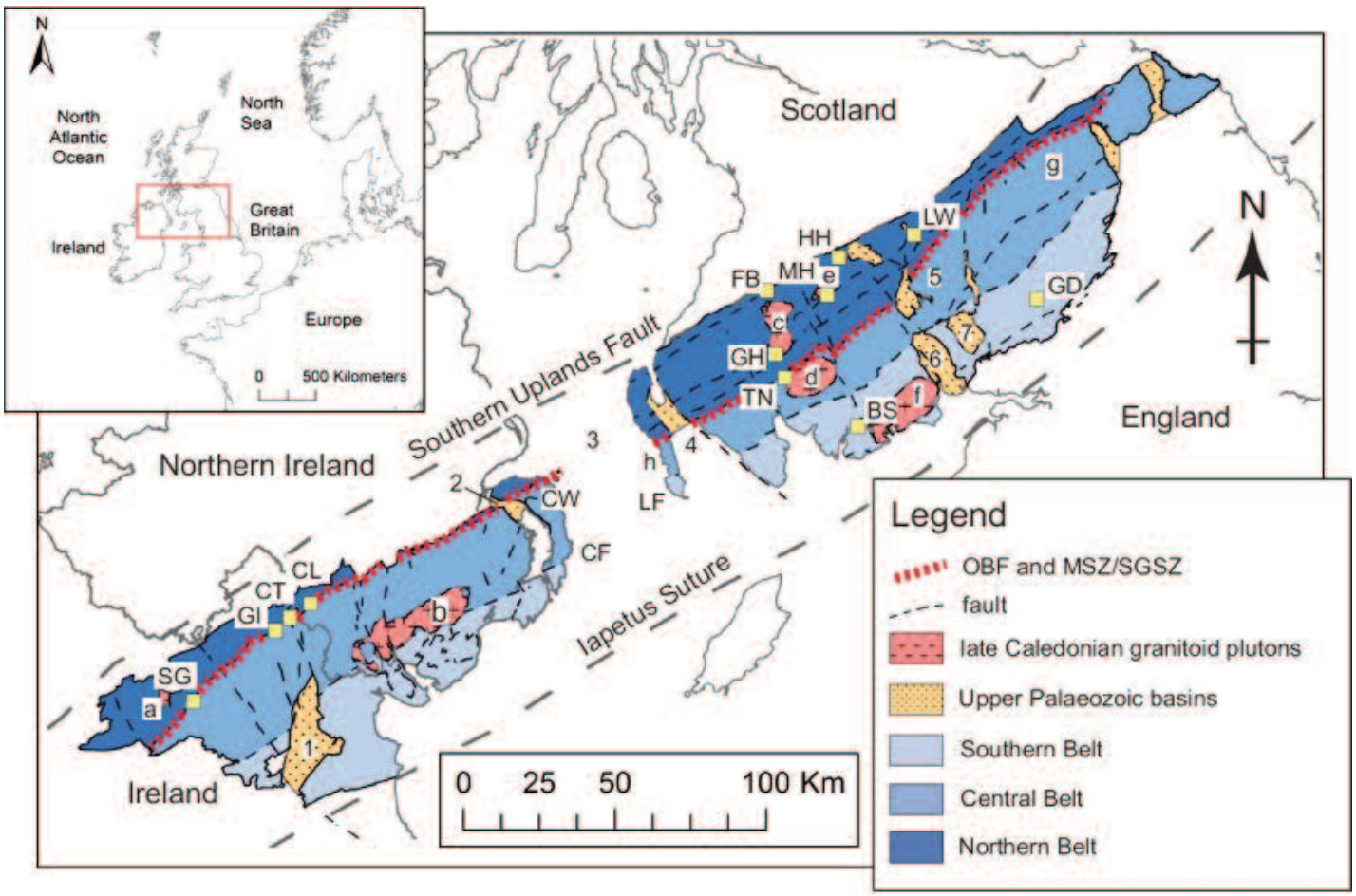


Figure 7 Map of the Southern Uplands-Down-Longford Terrane showing key features and locations: BS=Black Stockarton; CL=Clay Lake; CT=Clontibret; CW=Conlig-Whitespots; FB=Fore Burn; GD=Glendinning; GH=Glenhead; GI=Glenish; HH=Hare Hill; LW=Leadhills-Wanlockhead; MH=Moorbrock Hill; SG=Slieve Glah; TN=Talnotry. Permo-Carboniferous volcano-sedimentary basins: 1=Kinscourt; 2=Strangford; 3=North Channel; 4=Stranraer/Luce; 5=Thornhill; 6=Dumfries; 7=Langholm. Caledonian plutonic complexes: a=Crossdoney; b=Newry; c=Loch Doon; d=Fleet; e=Cairnsmore of Carsphairn; f=Criffel-Dalbeatie. Named structures: CF=Cloughy Fault; LF=Laurieston Fault; MSZ/SGSZ=Moniaive Shear Zone and Slieve Glah Shear Zone; OBF=Orlock Bridge Fault (from Rice and Cuthbert [in review], based on data provided by the BGS Licence No. 2015/162 ED © NERC).

arc rocks suggests that the original more distal fore-arc basin, which should have intervened between them, is also buried under this thrust.

Overall, the evidence suggests that Iapetus had closed by about 420Ma (latest Silurian), hailing the new regime of intramontane basins, gravelly rivers and landlocked lakes nourished by the Devonian mountain chain to the north — the age of the Old Red Sandstone (ORS).

Convergence between the SULDC and the LLT might have begun head-on, but quickly evolved into highly oblique 'docking'. Sinistral strike-slip motions continued for some time after collision, causing sinistral slip along the tract-bounding thrust faults, the development of a set of strongly oblique folds and a set of wrench faults at a high angle to the early thrusts. These elements formed two fracture sets (cross-faults) trending NNE and SE, which had an important influence on further structural development of the Southern Uplands and the evolution of its magmatism and mineralisation.

The first was the formation of small, fault-bounded, early Devonian Lower ORS basins such as those in Duns and Lauderdale east of Girvan (*see* Fig. 1), when these fractures were reactivated during a period of sinistral transtension 420–400Ma. Transpression and uplift followed 400–390Ma, known as the 'Acadian Orogeny' from the Appalachians of eastern Canada, where it was more intensively developed from the collision of Armorica (another Gondwanan microcontinent). This second period of compression explains the folding of the Lower ORS in southern Scotland and the absence of Middle Devonian strata, and was also the cause of widespread cleavage development in the Lake District, including the famous green slates.

A major structural feature of the SULDC related to sinistral transcurrent motion is the Moniaive shear zone (Fig. 7), a zone of mylonite up to 5km wide striking parallel to a line from the North Sea coast near Dunbar via the Rhinns of Galloway to near Cavan in Ireland. It is closely followed, and partly excised, by the Orlock Bridge Fault, a later brittle structure. This structure might have been active during the accretion stage but was certainly acting as a sinistral zone of ductile shear 410–390Ma, as it deforms porphyroblasts in the aureole of the Fleet granitoid pluton but is overprinted by hornfelsing caused by later intrusions from the same pluton. In fact, the Moniaive Shear Zone is closely associated with granitoid intrusion and both it and the Orlock Bridge Fault are associated with mineralisation, particularly gold. The change in the deep basement from Avalonian to Midland Valley type, as imaged by deep geophysical sounding, roughly coincides with the Moniaive Shear Zone, which may be related to relative motions of these two blocks during and after the collision. Clearly this structure taps into deep levels in the roots of the orogen.

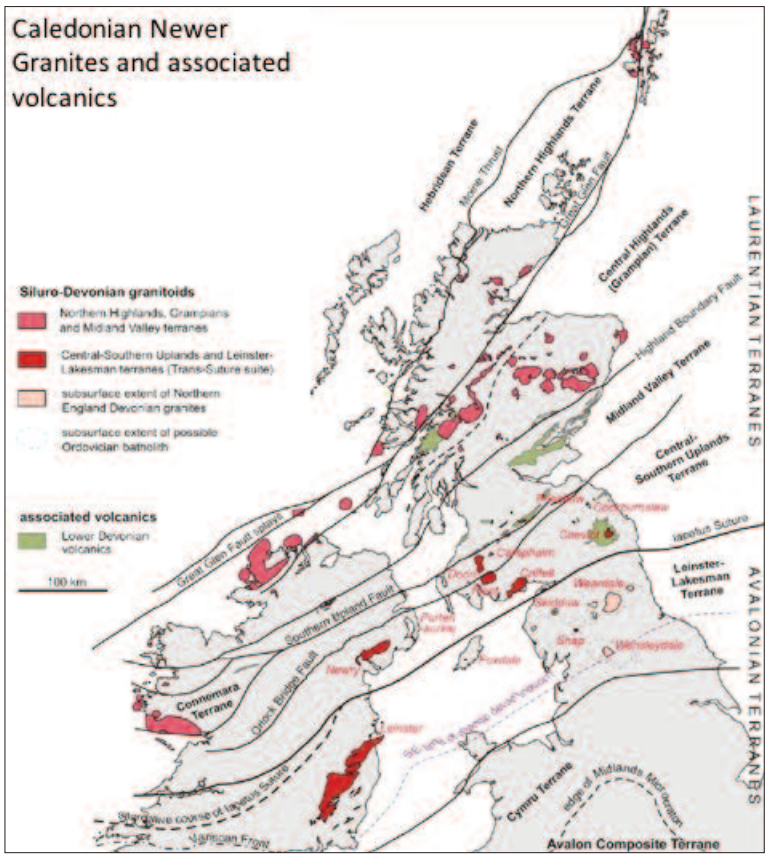


Figure 8 Late Caledonian granite plutons and associated volcanics of the northern British Isles in relation to terrane boundaries and the Iapetus Suture. Plutons mentioned in the text are labelled in red (modified after Miles et al. *2016, fig. 1).*

The collision of the Gondwanan terranes with Laurentia caused major changes in the structure and lithology of the Southern Uplands and provided new environments for mineralisation. The transtensional reactivation of structures in the accretionary prism and associated cross-faults opened pathways for mineralising fluids and were probably an important control on magma uprise and emplacement, as was the Moniaive Shear Zone. The sedimentary basins buried under the SULDC by thrusting, such as the Skiddaw Group (*see* Fig. 5), could have provided sources of metals for mineralisation. If enough of the structural factors coincided they could have led to the formation of ore deposits, but the igneous rocks of the Southern Uplands also played an additional, important role in generating the region's mineral riches. If the collision had been more head-on and less oblique the resulting crustal thickening and uplift might have led to the loss by erosion of much of the SUDLC and, with it, its ore deposits!

Late Caledonian magmatism

A glance at the geological map of the British Isles will draw your attention to the swarm of red blobs in Scotland and north-west England (Fig. 8). These are large intrusions (plutons) of granitoid rocks, most of which were emplaced in a surprisingly short interval during the Late Silurian and Early Devonian 430–390Ma. They are traditionally called the 'Newer Granites'.

Across northern Britain their composition reflects the basement geology beneath and around their outcrops. Those in the Southern Uplands, along with their neighbours in northern England, also have a distinctive local lithology. The group is called the 'Trans-Suture Suite' because it straddles the Iapetus Suture, some outcropping on the suture itself. The same suite extends into Ireland, including the Newry Pluton and Leinster Batholith (the largest of them all). Some are larger at depth, like the Lake District Batholith, and some are hidden in the subsurface, such as the Weardale Granite under the north Pennines and the enormous 80km long Tweeddale Pluton under the eastern half of the Southern Uplands. Three-dimensional geophysical modelling shows that these granitoid plutons are flat-topped and steep-sided with a bell-jar or tooth-like form; they extend *c*. 10km below the surface and represent prodigious amounts of magma that would have had a major effect on the surrounding rocks. They clearly tapped a large source of magma at great crustal depth or deeper. Granitoids and their igneous relatives are well known worldwide for their associations with economic metal ore deposits, and some aspects of the mineralisation in the Southern Uplands implicate igneous rocks in their genesis.

Individual intrusions are classic examples of zoned granitoid plutons in which the rocks are more evolved and younger inwards. For example, the Loch Doon Pluton (Fig. 9) has a discontinuous rim of diorite and tonalite, a complete concentric zone of granodiorite and a core of granite. Other plutons in Galloway follow a similar pattern, with variations in the

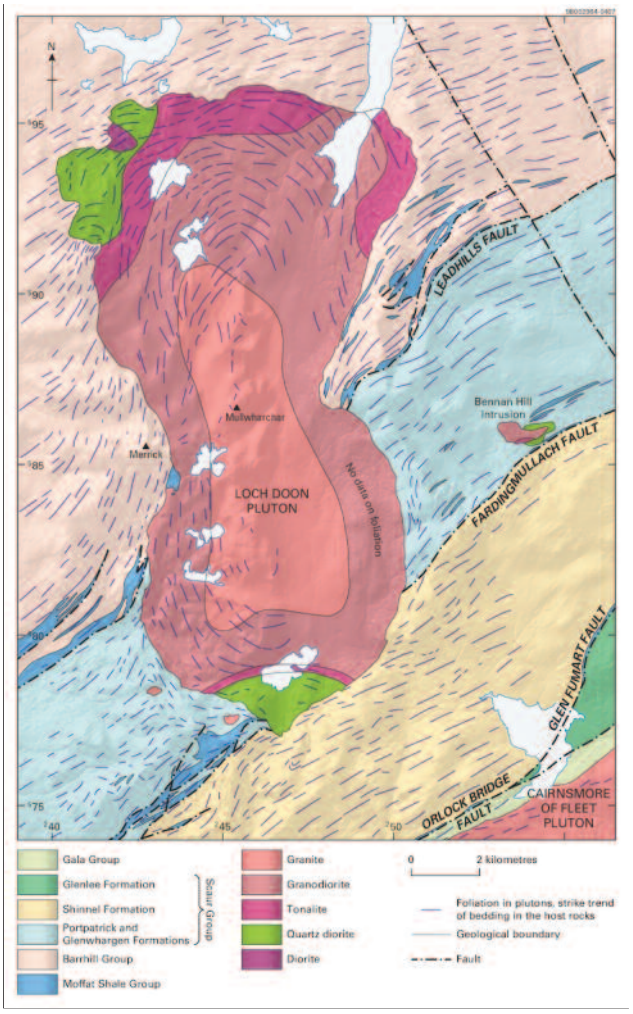


Figure 9 The zoned Loch Doon Pluton of Galloway (BGS image catalogue number P912342) (http://earthwise.bgs.ac.uk/index.php?title=File:P912342.jpg&filetimestamp=20150726172446&).

development of outer diorites and in the size of the granitic core. Intrusion in each pluton has occurred during a long time; for example, the main intrusion phase in Galloway was 416–410Ma, but the inner zone of the Fleet Pluton was intruded at 387Ma. The main phase coincided with the period of transtension and Lower ORS deposition, aided by motion on the Moniaive Shear Zone, which probably helped to provide conduits for magma uprise and create the space for the intrusion of these great masses of magma. In addition to the large plutons in Galloway and Ireland, there are numerous small stocks with a similar suite of rock types scattered along the Southern Uplands as far north-east as the Lammermuir Hills. Several are associated with mineralisation, some of which has been mined.

Chemical and isotopic 'fingerprints' show that dioritic to granodioritic rocks originate mainly from melting mafic lower crust or mantle, while the granitic cores had a larger contribution from melting of crust with a significant sedimentary component. The large contribution of metasediment to the magma is a peculiar feature of the Trans-Suture Suite granitoids compared to the granites in the rest of Scotland. They are, of course, surrounded by the sedimentary rocks of the SULDC greywackes and black shales, but at outcrop they show little sign of melting or assimilation into the magma. A deeper source within the SULDC is possible, but their isotopic composition actually precludes a local sedimentary source and suggests a source similar to the Skiddaw slates and Avalonian basement, which geophysical evidence suggests lies directly underneath.

Equally significant, but less obvious, is a swarm of hundreds of dykes in the Southern Uplands. They are roughly coeval with the major granitoid plutons and are distributed throughout the SULDC but tend to be more common in the southern tracts. There are two groups: a more felsic set of microdiorite to microgranite, which tend to be concentrated in the north; and more mafic dykes rich in mica or amphibole called lamprophyres (abundant biotite mica makes them glitter) (Fig. 10).

Rocks of the first group are sometimes confusingly referred to as 'porphyrites' and 'porphyries', significant because microdioritic porphyries are often associated with copper and gold mineralisation in other parts of the world. This group has compositions and probable origins similar to the rocks in the large plutons and minor intrusions. Rocks of the second group are abundant in the south and form a swathe from eastern Ireland to near Dunbar, slightly oblique to the Iapetus Suture. Their intrusion spans the end of the accretionary deformation and the transition into collision and transtension. Their great number and broad distribution suggests that large volumes of magma were present below the orogen, and hence large amounts of heat energy were carried up with them. Lamprophyres have often been associated with gold ores, but it has proved difficult to make a direct connection between their magmas and gold ores. However, an amphibole-rich group, the familiar appinites, are associated with copper-nickel ores and concentrations of gold and platinum.

Figure 10 Lamprophyre dykes (with hammer resting on dyke rock), Portcastle Bay, Whithorn (photographer Simon Cuthbert).

A cluster of lamprophyre dykes, other dykes, sheets and stocks of microdiorite and microgranodiorite at Black Stockarton Moor near Kirkudbright formed in a subvolcanic complex about the same time as the adjacent Criffel and Bengairn plutons. The presence of breccia pipes suggests a high crustal level at which magma releases volatiles, causing high-velocity gas streaming along fractures and pipes. A 1970s survey by the BGS found that the rocks had been intensely altered by water and carbon dioxide-rich fluids and have locally high copper concentrations and some high gold values. These features and associated porphyritic microdiorites and copper ores resemble subvolcanic 'porphyry copper' deposits, which elsewhere in the world host some of the largest copper and gold mines. Black Stockerton Moor does not appear to be an economically viable deposit, although there is scope for further exploration to reveal more.

Lamprophyres are thought to originate by partial melting in the mantle, but their potassium-rich, hydrous composition is different to the basalt magmas that we normally associate with mantle melting. The difference is that their mantle source has been metasomatised — chemically modified by the addition of alkalis and water. Subducted oceanic crust and its cover of pelagic sediments provide such contaminants. If the mantle wedge gets hot enough, they act as a flux, triggering melting in the hot mantle wedge between the top of the subducting slab and base of the overlying upper plate. Subduction of a large oceanic plate adds a lot of water and alkalis to the wedge, making it fertile for melting. The lamprophyric magmas rise and temporarily pond at the base of the crust, where they transfer heat into the overlying crust, causing large-scale melting and the generation of granitic melts. Both types of melt rise to form the lamprophyre dykes and the granitoid plutons in which the range of lithologies is controlled by differentiation of the primary lamprophyre magma and mixing of lamprophyre with the crust-derived granite.

Magmatism in a subduction system usually results in rocks of a calc-alkaline composition. The granitoids, diorites and lamprophyres in the Southern Uplands have calc-alkali-like compositions but also show key differences. Also, we might expect a large span in the ages of the igneous rocks in a magmatic arc that existed for *c.* 40Ma in the SUDLC. However, the magmatic period was a shorter outburst lasting less than 20Ma in the early Devonian during and just after collision with the LLT. There is little sign of Ordovician magmatism in southern Scotland. There is also a problem with the distribution of magmatism, because it extends across the Iapetus Suture and into the LLT (shown by the Shap, Skiddaw and Leinster granites).

How can we explain this?

The current thinking is that after the Avalonian collision jammed the throat of the subduction zone the dense oceanic lithosphere broke away from the continental lithosphere and tore off some Avalonian lithospheric mantle (Fig. 11). This rupture opened a gap in the subducting lithosphere through which hot asthenospheric mantle protruded. The heat thus introduced to the mantle wedge caused it to fuse — its melting point already lowered by metasomatism — and generate lamprophyre magma. This process underplated the sub-LLT and sub-Laurentian crust and the heat melted the lower crust to generate granitic magma by melting the Avalonian basement and its Skiddaw group sediment cover. The trans-tensional collision zone above opened pathways for magma to the upper crust and surface.

Two important aspects of this model are relevant to economic mineralisation. First, metasomatism ensures that the magmas derived from it will be rich in volatiles, especially water. When such melts eventually arrive near the surface the water will boil and escape from the melt, and so be available to dissolve and scavenge metals from the surrounding crust or bring out sulphur and metals from the melt. Second, metasomatism can enrich the mantle wedge in sulphur and metals, in addition to those already present in the mantle. This sulphur would then be available to mobilise metals and carry them to sites of ore precipitation. The sulphur can take at least three forms: dissolved in the lamprophyric magma, un-mixed from the magma as blobs of a separate metal sulphide melt or dissolved in hot water when the volatiles boil off from the magma near the surface. Un-mixing sulphide melt is a potent way to scavenge metals from magmas because they have a stronger affinity for sulphide melts than for silicate magmas. The fate of the metals then depends on when this un-mixing happens. Sulphide melts are dense, so if they un-mix early and deep from the lamprophyre melt. The sulphide sinks and never carries the metals to the surface to become ore. However, if the sulphide un-mixes late and shallow it might be emplaced in an upper crustal magma chamber and become ore or be entrained into water vapour when the magma boils in the volcanic realm and be deposited in hydrothermal veins.

The sources of sulphur can be identified by measuring the isotopes of sulphur in sulphide minerals. They show that some sulphide in the Southern Upland ore associated with igneous rocks does have a mantle origin, but there is a paradox in the hydrothermal sulphides. Other isotopes — such as lead and hafnium — in silicate rocks show that melting of a Skiddaw Slate-like source generated more evolved granites. But, although Skiddaw Slate sulphides have a distinctive sulphur isotope composition, the Southern Upland sulphur isotopes do not share this signature. Instead, Southern Upland sulphur is similar to that found in the Southern Upland sedimentary rocks such as the Moffat Shale. The resolution of this conundrum is not yet clear, but it is possible that interactions of lamprophyres with Skiddaw Slate (a sulphide-rich and chemically reduced lithology) caused the sulphide to un-mix and be dumped, losing the sulphur and its load of precious metals. The non-mantle sulphur in the ore veins is probably sourced from the local SULDC greywackes and shales, stripped out by deep-level assimilation into the magma as it entered the accretionary prism, or, more likely, was leached by hot water from the magma or the country rocks.

This intense flare-up of magmatism associated with continental collision made an important contribution to forming the crust

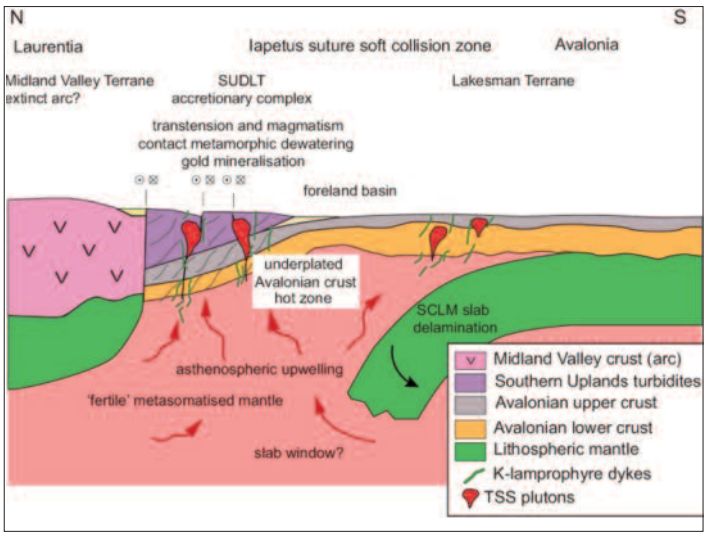


Figure 11 Model for the geodynamic setting and regional scale controls of Caledonian gold mineralisation in the SUDLT; 'SCLM' = sub-continental lithospheric mantle (from Rice and Cuthbert [in review] based on Miles et al. *2014, 2016).*

of southern Scotland and Ireland, the large granites underpinning the modern landscape. These granites show a close relationship with many ore deposits (although there are some important exceptions). They provided heat to generate fluids and drive fluid flow around plutons and are thus potentially significant for ore deposit genesis. The magmas carried dissolved volatiles capable of leaching and mobilising metals; the magmas themselves were potential sources of primary mantle sulphide and metals; the magmas could have scavenged sulphur and metals from the rocks through which they passed or around the magma chamber where they finally collected; and the ubiquitous occurrence of igneous rocks suggests a region-wide heat source that could have intensified metamorphism in the accretionary prism and hence generated ore-forming fluids. The coincidence of slab rupture and transtension led to the generation of huge volumes of ore-fertile magma and pathways for their emplacement in the crust. The 'soft-collision' model for this part of the Caledonides is being recognised in other orogenic belts as significant for ore deposit exploration, so perhaps Southern Uplands geology has something to teach the world in this respect.

The structural control of igneous intrusion by fault systems that developed during the subduction and collision stage was an important part of this story. These structures continued to play a role after the magmatism and volcanism subsided, as southern Scotland came to lie deep within the supercontinent of Pangaea.

Hidden valleys of Pangaea: post-Caledonian basins

After the Caledonian Orogen northward drift from southern tropics through the equatorial zone and into northern subtropical deserts dominated the story of the Southern Uplands. The collision of Laurasia with Gondwana during the Carboniferous progressively isolated Scotland from the world ocean, so that by the Permian Period Scotland lay within an enormous desert. From the late Devonian to the Triassic the Southern Uplands were bounded by the Midland Valley and Solway-Northumberland basins, while southern Scotland where the SULDC had assembled persisted as higher ground. In the early Devonian some north–south trending fault basins had formed. By the mid-Carboniferous a set of new, small, north-trending

transverse rifts had formed in the western half of the region, cutting across the Caledonian trend of the Southern Uplands-Longford-Down Terrane (SULDT), including the Sanquhar, Thornhill, Dumfries and Stranraer basins (orange and/or pale grey patches in Fig. 1). These can still be detected in the modern landscape as the Border hills rising abruptly in north-trending scarps above the more fertile low ground over the old rifts. The basin structure was 'trap-door' style, with a major fault on one side and smaller faults or a hinge-fold on the opposite side. Carboniferous deposition was shallow marine with early carbonates and later coal measures. In the Permian this was replaced with aeolian dune sandstones and sedimentary breccia fan deposits along the fault scarps (Fig. 12). These became some of the most well known rocks in Scotland — the red sandstones that are such a familiar part of the urban cultural landscapes of towns and cities from Carlisle to Glasgow. The Permian landscape in which they were laid down would have resembled some of the desert basins in the US Southwest, such as Death Valley.

In the nearby Midland Valley basin basaltic magmatism and volcanic activity accompanied rifting at several stages from the early Carboniferous to the early Permian and alkali basalt eruptions marked the earliest Permian in the Thornhill Basin.

During most of this time the basin-bounding faults probably provided pathways for penetration of saline and oxidising groundwaters into the subsurface beneath the basins. Chloride-rich waters like these are capable of liberating and transporting precious and base metals and, potentially, depositing them in veins to form ore deposits. It is interesting to see that the lead- and zinc-ore vein system at Wanlockhead and Leadhills lies between the Dumfries and Thornhill basins and the Snar Basin and aligns with the fault trends in the Thornhill Basin, so perhaps the ore vein system around Leadhills is the deep 'plumbing' of another late Palaeozoic basin that has since been removed by erosion.

The basement rocks under these basins may have been fertile sources of metals. For example, the greywackes often contain abundant pyroxene and spinel, which would have supplied lead and zinc, respectively. Metals might have enriched the late Caledonian granites and their envelopes and these might have been available for further concentration during later basin formation. Within the basins themselves the Permian basalt volcanics might have been a fertile source of economic metals held within their sulphides. The latter is significant as a source for gold and platinum metals. Recently developed ideas about red-bed systems show that oxidising saline groundwaters such as those under desert basins, can release gold from sulphides. When the fluids come into contact with less oxidising chemical environments, such as black shales or greywackes, the gold is likely to precipitate. The most favoured place for this would be a basin-bounding fault where red-bed sediments are faulted against a greywacke basement. This is exactly the situation in the Thornhill Basin, and a BGS study in 1996 found alluvial gold close to the eastern bounding fault.

The Permian–Carboniferous basins exploited older, collision-related structures and provided a new environment for ore deposit genesis. Groundwater in these basins had the potential to scavenge metals from the basement and from the basin fills themselves, and this might have been the source of some of the most productive mines in Scotland.

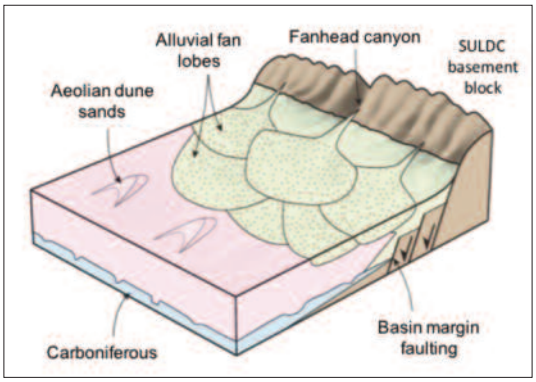


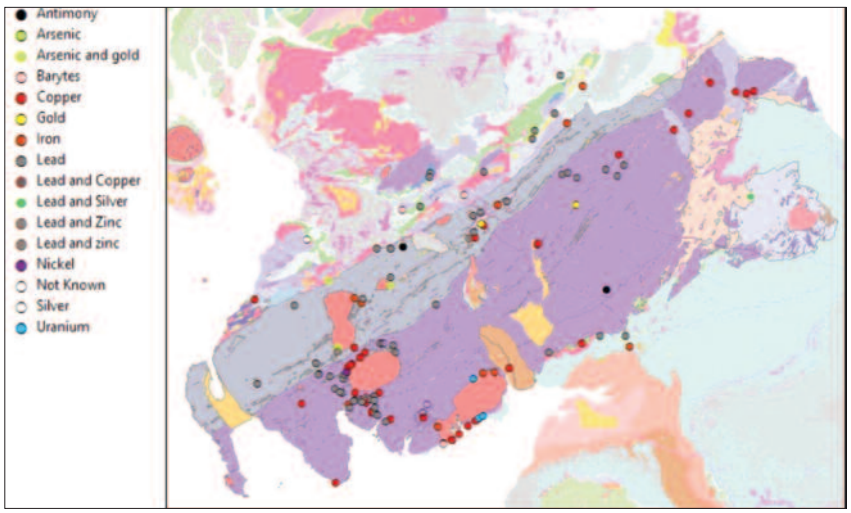
Figure 12 Schematic, simplified block model of a Permian transverse basin margin (based on the Carlisle Basin) (modified after BGS image catalogue number P912363) (http://earthwise.bgs.ac.uk/index.php?title=File:P912363.jpg&filetimestamp=20150726174527&).

Mines and miners

There has been mining in the Southern Uplands since medieval times, and possibly earlier. There are no active metal-ore mines here now, but the landscape is littered with the remains of old mine workings. A range of metals was mined or sought in trials, including lead, zinc, gold, antimony, arsenic, nickel, copper, silver, uranium, iron and barites. In contrast, in Ireland a large zinc mine is operating at Navan, Co. Meath within Carboniferous limestone unconformably overlying SULDC basement and an exciting gold find is being developed at Clontiret in Co. Monahan, on the Orlock Bridge Fault.

Following is a selection of mine locations and other sites that have been explored but not yet mined, described to illustrate the different types and styles of mineralisation in the Southern Uplands (*see* Fig. 7 for locations). Figure 13 shows that the most common types of ore mined are lead-zinc deposits and copper. Although the former often had large outputs, copper was often in small, short-lived operations. A large cluster of mines and trials surrounds the Galloway plutons, some scatter along the northern margin of the Solway-Northumbria basin, while most of the remainder are spread over the northern and

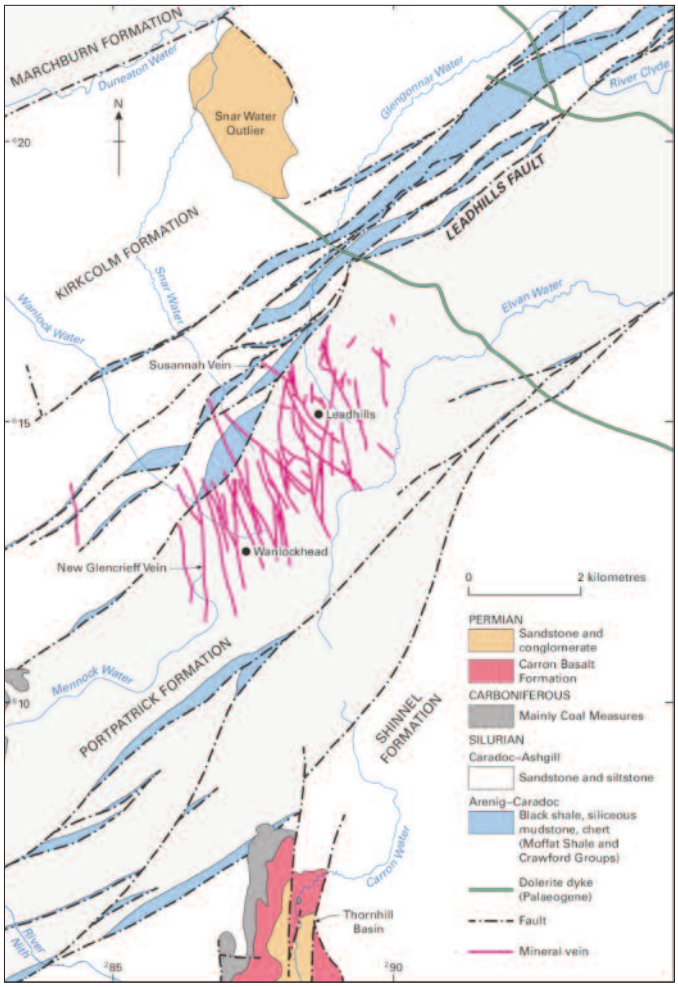
*Figure 13 Mine locations in Southern Scotland with ore types (*data from *https://www.aditnow.co.uk with additional unmined discoveries from MRP reports. Base map data provided by the BGS Licence No. 2015/162 ED © NERC; for details of geological units see http://mapapps.bgs.ac.uk/geologyofbritain/home.html?).*



central parts of the SULDC, including a group spread out along the Leadhills imbricate zone.

Talnotry, near Newton Stewart is an example of a sulphide ore of purely magmatic origin. A nickel mine was worked in about 1885. The ore is hosted in a small sill-like mass of diorite that probably has affinities with appinite-type lamprophyre. It lies close to the western margin of the Fleet Pluton but predates it. The diorite hosts nickel-copper mineralisation near its base with nickelite (NiAs), gersdorffite (NiAsS), pyrrhotite (FeS), pentlandite (Fe,Ni)S and chalcopyrite ($CuFeS_2$) occurring as blebs in among the amphibole, plagioclase feldspar, biotite, chlorite and quartz of the diorite. The ores are enriched in platinum group elements (platinum, palladium, rhenium, iridium) and gold; *c*. 100 tonnes of ore was extracted but little was removed from the site and none was processed. The ore probably crystallised from sulphide and arsenide melts segregated from an appinite (lamprophyre) magma derived by partial melting of metasomatised mantle.

Black Stockarton Moor is an area of copper-molybdenum mineralisation where it resembles porphyry copper-gold ore deposits in subvolcanic igneous complexes. Here Silurian Hawick Group greywackes are enriched in pyrite, chalcopyrite, bornite and molybdenite in veins and disseminated through intense hydrothermal alteration haloes around porphyritic microgranodiorite sheets. No attempts have been made to mine it since its discovery during BGS exploration in the 1970s. Another well exposed example of porphyry copper style mineralisation is at Cairngarroch Bay on the west coast of the Rhinns of Galloway.



Porphyry copper-molybdenum-gold deposits are among the richest sources of these metals in the world and are currently the subject of intense research and the mining industry. They form in calc-alkaline granodiorite plutons and below the volcanic edifice above it. In the magma chamber roof a small mass of magma appears to intrude upwards, eventually solidifying to form a stock or intrusive sheet complex of porphyritic microdiorite or microgranodiorite (one of these is forming right now under Mount St Helens in the Cascades of western USA). As the magma solidifies, water that cannot enter the crystals builds up and boils off to form a saline, sulphide-rich watery fluid enriched in metals owing to high chloride content. The fluid pressure builds up and ruptures the margins of the stock and the country-rock envelope creating a network of fractures in which metal sulphides precipitate. The surrounding rock is intensely altered by the magmatic fluids and local groundwater heated by the intrusion, and this is also mineralised. The metals drop out of solution in a particular order, usually with copper and molybdenum first, then lead and zinc as the fluid is cooled. If gold is present it can precipitate across a range of temperatures. In this type of mineralisation the metals have their source in the magma (and hence in the mantle or lower crust where it originated), but as the hydrothermal fluids come into contact with the country rock they may scavenge metals from them and create sulphides that have a mixed origin.

Breccia zones associated with copper-molybdenum mineralisation at Black Stockerton Moor are also locally enriched in arsenic (as arsenopyrite), antimony (as stibnite) and gold. Other examples of As-Sb-Au mineralisation are known in the SULDC, especially from Glenhead Burn on the margins of the Loch Doon Pluton, Moorbrock Hill at the margin of the Carsphairn Pluton and also at Hare Hill, just north of the Southern Upland Fault. At Hare Hill, zoned As-Sb-Cu-Pb-Zn mineralisation is associated with intensely altered granodiorite. Trial workings have been attempted here in late-stage antimony-lead veins whose metal source might be in the mineralised granodiorite. Such deposits are examples of 'mesothermal' ores that formed at deeper levels in the magmatic-volcanic system but might overlap with the porphyry system as at Black Stockerton Moor.

Louisa Mine is near Eskdalemuir in the central Southern Uplands, well to the east of the Galloway plutons. Here *c*. 200 tonnes of antimony ore was produced from the late 18th century. The remains of the mine buildings and entrance can still be seen. The ore veins cut Silurian greywackes of the Hawick Group. The principal ore mineral was stibnite along with antimony minerals, including tetrahedrite. They coexist with pyrite, arsenopyrite, galena, sphalerite and chalcopyrite, the arsenopyrite being enriched in gold. Interestingly, there is no sign of igneous activity here, and it is possible that the source of antimony and arsenic was nearby conglomerate debris flow units within the greywackes, which may have originated during or shortly after deposition. However, the alteration style associated with the ore veins is similar to that in Galloway associated with granitoid plutons, so perhaps there are hidden intrusions below outcrop level.

The Leadhills-Wanlockhead area (Fig. 14) in the Lowther Hills was Scotland's most productive lead mining area. Lead and zinc were worked for several centuries, the original charter being

Figure 14 The Leadhills-Wanlockhead ore field vein system in relation to the Thornhill and Snar Basins (BGS image catalogue number P912377) (http://earthwise.bgs.ac.uk/index.php?title=File:P912377.jpg&filetimestamp=20150726174537&).

granted to monks of Newbattle Abbey in 1293. Mining ceased in 1960s. From the 17th to 20th centuries more than 70 veins were worked, producing more than 400,000 tonnes of lead metal, 10,000 tonnes of zinc and 25 tonnes of silver. At its zenith this mine produced 90% of Scotland's lead. The legacy of mining is clearly visible in the landscape, which was transformed by the infrastructure and mine spoil that sometimes filled the valley floors to a depth of many metres. Lead-zinc-silver ores are hosted by a system of N–S and NW–SE trending fractures and faults cutting Portpatrick Formation greywackes and Moffat shales of the Leadhills imbricate fault zone. These vein trends are another example of the structural inheritance of the late Caledonian transverse fault systems. The veins mostly terminate northward against the Moffat shales, and it has often been speculated that this formed an impermeable barrier to fluid flow.

The primary ore minerals in the Leadhills-Wanlockhead ore field are galena, sphalerite, chalcopyrite and pyrite, plus rare marcasite, niccolite, rammelsbergite and cobaltite. Gangue minerals (non-economic minerals coexisting with the ore) include ankerite, calcite, barytes and quartz. This area is famous for a rich assemblage of secondary minerals created by reactions of the primary ore minerals with oxidising groundwaters, including some discovered locally such as leadhillite, caledonite and suzannite. More than 60 secondary minerals have been named and the area has become a mineral collector's paradise (for those with the patience and sharp eyes to find them).

The timing of Pb-Zn mineralisation is not well constrained, but was probably Carboniferous to Permian. As we have seen, a likely source for the ore-forming fluids was meteoric water percolating from an overlying sedimentary basin. However, when we take into consideration the local abundance of alluvial gold and its possible sources a more complicated situation becomes likely in which the Pb-Zn veins have, at least in part, an older history.

The other major area of lead mining was in Galloway, near Newton Stewart and Carsphairn. Copper was also produced here, for example in the Pibble mine, where the mine buildings can still be seen. The proximity to the late Caledonian granitoid plutons suggests a magmatic-hydrothermal origin, but the north–south trend of the veins is similar to Leadhills and there is some evidence for a syn- or post-Carboniferous history, so perhaps the plutons pre-concentrated the lead and copper, which was further concentrated during later reactivation of the old transverse faults during the late Palaeozoic rift-basin episode.

Leadhills and Wanlockhead centres have also been important for alluvial gold working for several centuries. It remains a popular area for recreational gold panning. The 16th century was the major period of gold extraction by miners such as George Bowes, Sir Bevis Bulmer and Stephen Atkinson. In the early 16th century there was sufficient gold being produced to contribute to the Scottish Crown Jewels and the minting of coinage, but the alluvium had largely been worked out by the 17th century. The gold can still be won quite easily in small flakes or nuggets by panning or sluicing the active stream alluvium. In the early days nuggets of up to 1kg were reported and occasionally nuggets of a few grams are still found, such as the 18.1g nugget found in 2015, reputed to be worth more than £10,000! Much of the stream gold appears to be sourced from alluvial terraces in the main river valleys around Leadhills, particularly from gravels resting on rock-head. The early miners explored for gold by the process of 'hushing' — damming large ponds of water at the tops of the valley sides, then releasing it all at once to scour the soil from the slopes (OS maps still bear terms such as 'gold scaurs'). Presumably the environment agencies would frown upon such practices today!

Modern microchemical techniques give clues about the likely bedrock sources of this enigmatic gold, and suggest that it comes from several sources, including mesothermal shear zones, dolerite dykes that cut through the area and arc debris from the source of the greywacke sandstones. No one has yet found any bedrock sources of the gold. Sixteenth-century miners like Bulmer and Atkinson claimed to have found gold in quartz veins and even worked them, but the locations are not well known and when some of the mines closed the workers were sworn to secrecy. Bulmer Moss, in the hills near Leadhills, could be a clue on the map to one such place.

An obvious source for gold is the lead-ore veins, but in spite of driving hundreds of metres of shafts and adits no visible gold has been found. Research in the 1950s suggests that there are, in fact, two generations of veins in the Leadhills-Wanlockhead area. An early set of quartz-sericite-pyrite / arsenopyrite veins is probably of late Caledonian age. These were brecciated during the later, main Carboniferous(?) episode of Pb-Zn mineralisation. This has been corroborated by later studies of vein quartz in various vein systems across the SULDT. The early vein set is thought to be associated with gold on the basis of comparisons with other gold-bearing veins in the SULDC. Another encouraging feature is that these early veins follow the transverse Caledonian Fault trend, in common with other gold-bearing systems like Hare Hill and Glenhead Burn, and the major gold discoveries around Clontibret in Ireland. Yet gold in such veins at Leadhills has not been found and even the early miners speculated that the gold has mostly been eroded away and now resides entirely in the alluvium.

Like the Louisa mine, the Leadhills-Wanlockhead alluvial gold area is remote from major Caledonian plutons. There are, however, numerous felsic, porphyritic dykes in the area, so a late Caledonian magmatic source is possible. This is also the case at Clontibret where there is no obvious magmatic source for the ore-forming fluids. However, there is some hornfelsing suggestive of a hidden intrusion in the subsurface.

'Gold-only' deposits like Leadhills-Wanlockhead and Au-As-Sb deposits that outcrop remote from major igneous intrusions suggest an association with a major group of gold-ore deposits known as 'orogenic gold'. The Southern Uplands has several characteristics like those at Phanerozoic orogenic gold terrains around the world, including the turbidite-hosted or slate-hosted context. The 'pure' version of such an ore-forming model suggests that the gold is released from sedimentary or igneous sulphides by fluids generated during metamorphism (especially at the greenschist facies to amphibolite facies transition) or dewatering of sediment in fore-arc accretionary prisms. If this occurred in the SULDC it must have been at much deeper and hotter levels that the present level of exposure, where the metamorphic grade is sub-greenschist. There is also clear evidence of a magmatic source for the ore in some gold-bearing deposits in the SULDC. The relative contribution of metamorphic and igneous fluids in orogenic gold systems is a matter of great debate at the moment.

The accessibility and detailed knowledge of the geology of the Southern Uplands makes it an excellent place to help shed some light on this debate.

Legacy

Mining in the Southern Uplands has ceased, at least for the time being. However, the exploitation of metalliferous resources in the Southern Uplands over hundreds of years has left an inheritance in the landscape, some negative, some positive, some obvious, some invisible and insidious. Like other parts of Britain, such as Cornwall, the infrastructure of mining is still visible in many places and has even become a tourist attraction. At Wanlockhead the excellent Museum of Lead Mining has preserved an old beam engine and part of the Lochnell mine, which it is possible to visit. Recreational gold panning in this area makes a small but significant contribution to the local economy. Yet the legacy of abandoned and ruined buildings among the spoil heaps is far from an attractive addition to this otherwise beautiful landscape. The villages of Leadhills and Wanlockhead are set in a landscape founded on lead-enriched made ground. This forms a major component of the soil eroded into the sediment of the local streambeds, causing raised levels of lead and other heavy metals in the water. Fortunately, the contamination is not as high as in some sulphide mining areas around the world because of the carbonate rich composition of the ore gangue, but it has still been necessary to provide a public water supply from outside the ore field. Some sites where arsenic- and antimony-bearing ores were extracted and smelted are, according to international standards, classed as highly contaminated (Fig.15).

Figure 15 The mine spoil heap and abandoned mine buildings of the Glen Crieff mine at Wanlockhead (BGS image catalogue number P266687; photographer R. Gillanders) (http://earthwise.bgs.ac.uk/ index.php?title=File:P266687.jpg&filetimestamp= 20150315212931&).

The future

The need for fresh resources for novel industrial applications and the allied need for national resource security is driving a new interest in indigenous resources in the UK and a renaissance in mining is taking place in other parts of the country, such as south--west England. The most recent systematic evaluation of metalliferous ore resources in the Southern Uplands was the BGS Mineral Reconnaissance Programme sponsored by the Department of Trade and Industry in the 1970s to 1990s. Some new deposits were identified, but none have yet proved to be economic. However, in the SULDC in Ireland, in the same geological context, major gold resources are being identified, so perhaps there is some reason for optimism for finding resources in Scotland. Or, perhaps some local factors such as the level or erosion mean that economic resources will never be found in the Southern Uplands.

It is possible that old mines might have new lives for different purposes, for example different metals than those originally extracted, or as sources of ground-sourced heat energy (similar to that being investigated in old coal mines in the Glasgow area).

If viable new resources are found, we might see a new industrial landscape developing in southern Scotland, in which case old interests might conflict with new ones. Perhaps, paradoxically, areas that depend on old mining for tourism might feel threatened by the opening up of new mines in the same place.

Even if the Southern Uplands has no new resources to offer, we are lucky to have a great deal of knowledge about the geology of this area, thanks to the excellent work of the BGS and generations of academic geologists. This makes the Southern Uplands well placed to enhance our understanding of ore deposits and make a contribution to current debates, and to train the British economic geologists of the future.

Acknowledgements

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A comprehensive picture of the Southern Uplands derives from a large number of sources. Rather than burden the text with numerous references, I here provide a short list of recommended reading along with cited sources.

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Book review

Moreno, T., Wallis, S., Kojima, T., and Gibbons, W. (eds) 2016 *The Geology of Japan*. London: The Geological Society. (paperback ISBN 978-1-86239-743-9, £50; hardback ISBN 978-1-86239-742-2, £100; 522pp)

It is interesting to compare New Zealand, Japan, and the British Isles – three archipelagos of much the same size. New Zealand has two large islands, each between Britain and Ireland in size; but it is the above sea level portion of an isolated mini-continent, and it is crossed by an active transverse fault that is a plate boundary. The British Isles have been an outlying portion of a large continent for almost all the Cenozoic, to which tectonic activity has been confined to intermittent periods of uplift leading to much erosion.

Japan's principal island, Honshu, is not much larger than Britain. Honshu beats Britain to ninth largest in the world, and it is curious that Britain is frequently referred to as 'a small island' (even sometimes as a 'tiny island'). The Japanese archipelago also has three medium-sized islands, of which the largest, Hokkaido, is slightly smaller than Ireland. On the other hand, while having — like New Zealand and the British Isles — significant reminders of earlier geological periods when some of its present landmass was part of a continent, it is basically a number of fused island arcs with an older basement. These arcs are related to four active destructive plate boundaries to the east and south, while another plate boundary, the Itoigawa-Shizuoka Tectonic Line, runs north-to-south separating the Amur Plate (not exactly part of the Eurasian Plate) from the Okhotsk Plate (not exactly part of the North American Plate).

This book is another of the Geological Society's 'Geology of…' series, which so far also includes Thailand, Chile, Central Europe, England and Wales, Spain, and Scotland. Like these other volumes *The Geology of Japan* has many authors — more than 70 – and brings up-to-date research into the geology of an area. It is the first comprehensive English-language survey of the geology of Japan for 25 years.

There are 12 main chapters: an overview of the geological evolution of Japan; regional tectonostratigraphy; ophiolites and ultramafic units; granitic rocks; Miocene–Holocene volcanism; Neogene–Quaternary sedimentary successions; deep seismic structure; crustal earthquakes; coastal geology and oceanography; mineral and hydrocarbon resources; engineering geology; and field geotraverse, geoparks and geomuseums (with information on travelling by public transport to see some of the great geological sites of Japan).

For those interested in island arcs and subduction zones, the sub-chapter on the Izu-Bonin(-Mariana) Arc system has some fascinating reflections on the creation and growth of continental crust at island arcs: "It is clearly absurd that the existence of continental crust is necessary for the creation of further new continental crust, yet the means by which the initial arc crust, composed of mantle-derived mafic magma, evolves into intermediate continental crust remains largely unknown" (p175). This question was posed more than 20 years ago at the beginning of Block 4 in the OU course S267 How the Earth Works: "Is it at island arcs that we can see the process of making continents from the mantle, caught in its early stages?"

The Izu Collision Zone in central Japan "is presently the only place on Earth where an active intra-oceanic arc is currently colliding with a mature, continental arc, providing a unique opportunity to study the geological processes that occur during arc-continent collision" (p192). This area is also where the magnitude 7.9 Great Kanto Earthquake of 1923 killed more than 100,000 people; and where the active Fuji and Hakone volcanoes are situated. I must confess to being surprised that Fuji, which from its appearance I have always thought of as a typical andesitic subduction-related strato-volcano, has in fact always erupted basaltic magma during its 100,000-year history.

Japan is for most people associated more with destructive earthquakes (and consequent tsunamis) than with destructive volcanic eruptions, and so the chapter on crustal earthquakes is of particular interest. Records go back unusually far, to AD 684, plus earlier descriptions, and the largest historical earthquake was as recently as 2011. I am a little astonished that although there is much about hazard assessment, there is no separate treatment of hazard mitigation. Tsunamis also have no separate treatment, though it is noted that after the 2011 Tohoku-oki earthquake and tsunami "a tremendous amount of tsunami studies have been conducted and reported" (p415).

In general, this book appears a most comprehensive and useful work, and I hope it will be much borrowed from the Severnside branch library.

— Philip Clark, MA Oxon, BSc (hons) Open

Map review

BGS, GSNI, GSI 2017 *Bedrock Geology of the United Kingdom and Ireland (Map) 1:1 250 000 Scale*. Keyworth: British Geological Survey (ISBN (flat), 978-0-7518-3795-7), (folded) 978-0-7518-3793-3); 1000mm × 760mm; £5.95)

This new map has been produced in collaboration with the Geological Survey of Ireland, the Geological Survey of Northern Ireland, the Earth Science Teachers' Association and the Geographical Association.

It is an attractive, boldly coloured map depicting the solid, bedrock geology of the United Kingdom and Eire; it is generalised from larger-scale maps and overlain on shaded relief. Suitable as a teaching resource for a wide range of educational establishments it would help to provide a good basic understanding of the diverse geology to be found in these regions on a single sheet. The one-sided sheet is substantially filled with the geology map, cross-sections, the Index and explanation, and lastly, four embedded boxes containing numbered 'Geological sites of interest' for each country. These sites are easily found on the map and the text throughout the sheet is fully readable and not obscured by the bold colours.

The three NW/SE-trending cross-sections covering England, Scotland and Eire each give an excellent overview of the deeper geology and structures, and should give any enquiring map-owner an incentive for further study. Major faults and thrusts are clearly displayed on both the map and in the cross-sections, but names have been omitted on the latter, presumably for clarity.

The relationship between the geology of the various islands is also well shown, but, with this in mind, I was disappointed to see that once again geology seems to stop at the English Channel and France is merely depicted as a white curve. As the French coast is so close to the UK at this point it would be of great interest, and provide an area for further study, to see how the geology either side of the Channel is closely related. My last suggestion is the lack of further information for the 'Geological sites of interest' or where to find it — perhaps a possible website could have been added.

Overall the map serves its purpose; the information is well defined, it encourages further investigation and provides fine value for money.

— Mrs Yvonne Lewis-Cutt, BA(Hons) OU

The origin of the Torridon and Moine in the foreland basin of the Grenville Orogen

Maarten Krabbendam

British Geological Survey, Lyell Centre, Research Avenue South, Edinburgh EH14 4AP

Introduction

The geology of the Northern Highlands of Scotland is dominated by two sequences of originally sedimentary rocks: the 'Torridonian' and the 'Moine' (Fig. 1). The Torridonian comprises a series of red sandstones and minor shales that overlie the Archaean–Paleoproterozoic basement of Lewisian Gneiss. Torridonian rocks occur solely west of the Caledonian Moine thrust, and are largely undeformed. Sedimentary structures are well preserved, and the rocks have been mainly studied by sedimentologists, who broadly favoured deposition in fault-bounded rift basins (Owen 2014; Williams 2001; Stewart 2002).

East and above the Moine Thrust, within the Caledonian Orogen, the Moine metasediments is an equally thick stack of siliciclastic rocks, but these rocks have mainly been studied by structural geologists and metamorphic petrologists (e.g. Ramsay 1962). Before 2000, the Moine was interpreted as being deposited in a shallow marine, fault-bounded rift basin (Strachan 1986; Soper *et al.* 1998). Although equivalence of the two rock packages was mooted by Peach (Peach and Horne 1930), in most handbooks these sequences are dealt with as strictly separate entities that had little to do with each other (e.g. Trewin, 2002; Stewart 2002).

Meanwhile in Canada, many Canadian geologists were asking themselves where the foreland basin to the Grenville Orogen was (e.g. Davidson 2008). The Grenville Orogen (Fig. 2), between 1,100 and 1,000 million years old, was one of the first continent–continent collisional orogens on Earth (e.g. Rivers 1997), and was pivotal in building the supercontinent Rodinia, the

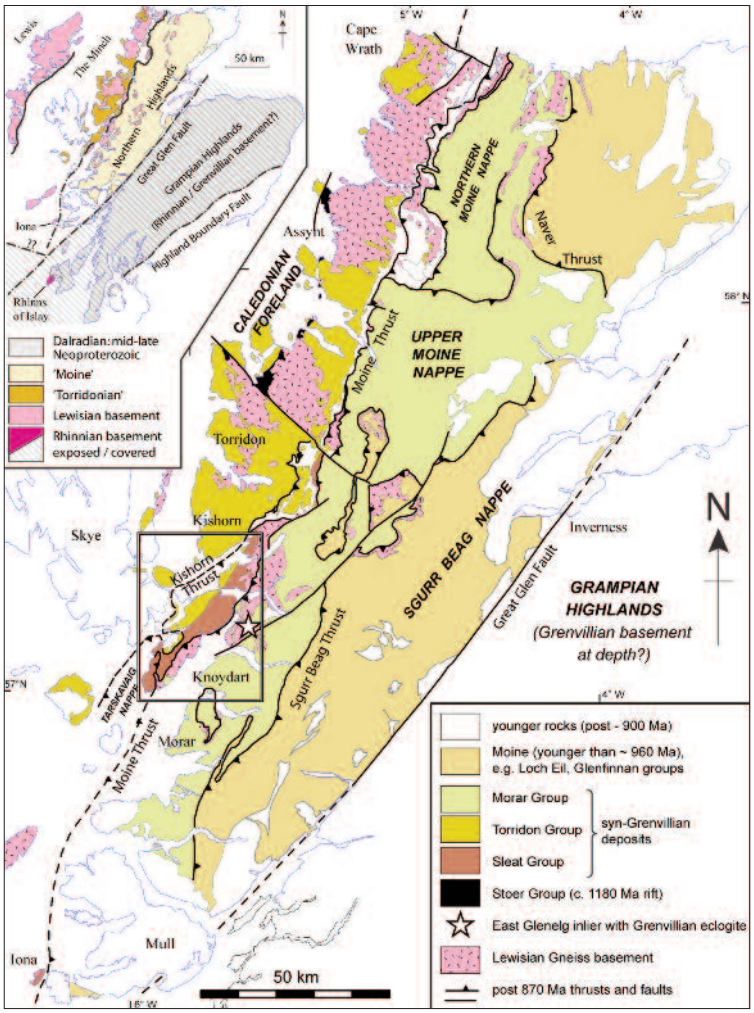
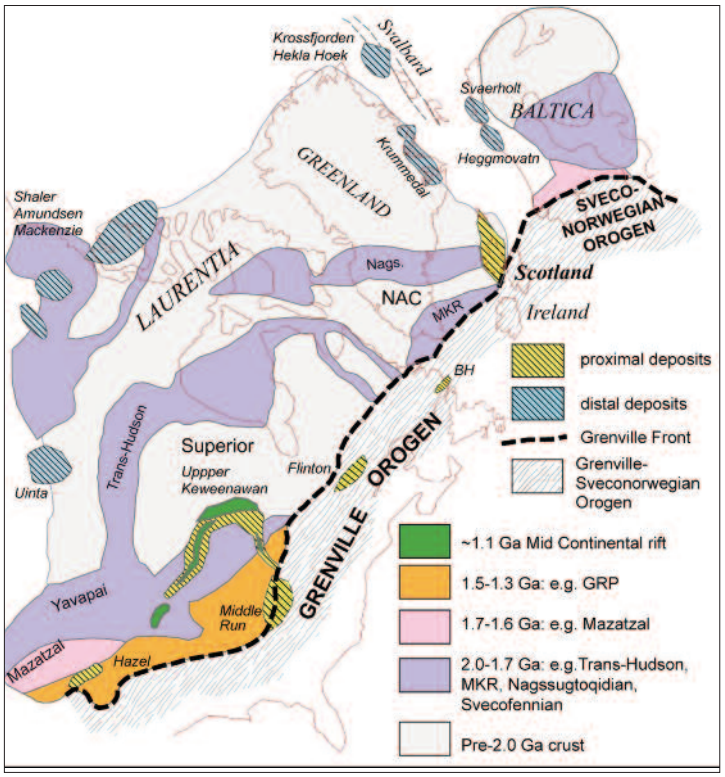


Figure 1 Simplified geological map of the Northern Highlands, highlighting the Neoproterozoic siliciclastic rocks. Simplified after British Geological Survey (2007) and Krabbendam et al. *(2008). Inset shows broad subdivision of Northern Scotland, including inferred extent of Rhinnian basement.*



Neoproterozoic version of Pangea. The Grenville Orogen was arguably the largest mountain range in the Earth's history in terms of the volume of crust affected by orogeny (van Kranendonk *et al.* 2013), dwarfing the Himalayas. The orogen stretched from Texas, across the eastern USA (where it was later re-worked in the Appalachians), into eastern Canada, where its metamorphosed crust underlies much of southern Ontario, Quebec and Labrador. As the Atlantic did not yet exist, the orogen crosses over underneath northern Ireland and northern

Figure 2 Schematic map of Laurentia and Baltica and the Grenville Orogen, showing a reconstruction at c. *1000Ma. Distal deposits are clastic deposits with detritus originating from the Grenville Orogen, but not deposited in a foreland basin* sensu stricto. *BH = Battle Harbour, GRP = Granite-Rhyolite Province, MKR = Makkovik-Ketilidian-Rhinnian orogens, NAC = North Atlantic Craton, Nags = Nagssugtoqidian orogen (see Krabbendam* et al. *(2017) and references therein).*

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Scotland (where a small remnant is recognised near Glenelg; e.g. Storey 2008) and from there into Scandinavia, where it is known as the Sveco-Norwegian Orogen and is exposed in southern Norway and south-west Sweden.

In Canada, the Grenville Orogen is well exposed (if completely eroded down to almost sea level) but, despite the size of the orogen, there is in essence no foreland basin preserved. Small remnants of foreland basins occur folded up within the Grenville Orogen itself, and some units in Ohio have been recognised as a foreland basin deposits, but are buried several kilometres beneath younger sediments and so are inaccessible. The Keweenawan deposits, exposed around the Great Lakes, contain detritus originating from the Grenville Orogen, but were deposited in the Mid-Continental Rift (analogous to the Rhine Graben with respect to the European Alps), and cannot tell us much about the foreland deposition. Distal detritus has been discovered in a number of places, for example in the northern Arctic islands of Canada and around Svalbard (Rainbird *et al.* 1997, 2012; Petterson 2009). Overall, there is no well-exposed, proximal Grenvillian Foreland Basin in North America that can be used to deduce the evolution of the basin.

It is thus not surprising that the idea that the Neoproterozoic rocks of Scotland may represent part of the Grenville Foreland Basin was first put to the test by a Canadian geologist, Rob Rainbird, who was the first to systematically study detrital zircon from the Stoer and Torridon groups (Rainbird *et al.* 2001). Rainbird concluded that the lower Stoer Group had exclusively zircons of Archaean–Palaeoproterozoic age, that exactly matched the Lewisian Gneiss, and were thus of local origin, compatible with a rift-basin origin as proposed by Stewart (1982). However, the Torridon Group contained Mesoproterozoic detrital zircons that did not match at all with older rocks in Scotland: instead they matched perfectly the age of a massive granite batholith that was uplifted in the Grenville Orogen. Thus, Rainbird *et al.* (2001) concluded that the Torridon Group was part of the Grenville Foreland Basin.

This article is a summary of work done over the last few years that builds on the original work of Rob Rainbird. With Helen Bonsor, Rob Strachan, Tony Prave, Graham Leslie, Kathryn Goodenough, John Ramsay, David Cheer, Matt Horstwood and Toby Rivers we mapped, logged, analysed and discussed the rocks of the Torridon, Sleat and Morar groups in northern Scotland. Below I will summarise the stratigraphy and sedimentology of early Neoproterozoic sequences in Scotland and the detrital zircon and rutile data from Torridon and Sleat groups. This research leads to the conclusion that the Grenville Foreland Basin includes the Torridon, Sleat and Morar groups in northern Scotland, and that these units show several phases of in-fill that can be used to constrain the overall foreland basin evolution.

Further details can be found in Krabbendam *et al.* (2008, 2014, 2017) and in Bonsor *et al.* (2010, 2012).

A foreland basin

For sedimentation to occur, there must be a basin — in essence a place for sediments to gather, for instance a rift basin or a delta. A foreland basin is a sedimentary basin in front of a mountain belt. Here the accommodation space is provided in large part by the load of the adjacent mountain belt: the mountain belt depresses the lithosphere and creates a depression adjacent to the mountains. As sediment sourced from the mountains accumulates in this depression, the cumulative load of this sediment depresses the lithosphere further, creating more accommodation space, causing an almost virtuous circle that may continue until the mountain building is exhausted. The Ganges Basin adjacent in the Himalayas is a classic present-day example of a foreland basin with up to 6km of sand and gravel deposited since the start of the Himalayan orogeny. Much sediment, however, may 'escape' the system, and is transported by rivers to more distal, usually marine basins. In the case of the Ganges, this river takes much of the fine sand and silt to the more distal Ganges Delta and Bengal Fan in Bangladesh. Such distal basins are not foreland basins sensu stricto*, as their subsidence is not primarily controlled by the load of the Himalayas.*

Stratigraphy of Northern Highlands

The Precambrian siliciclastic rocks of the Northern Highlands can be suitably subdivided into the following groups, from west to east (Figs 1 and 3, *opposite*):

- The Stoer Group, at *c.* 1180Ma, this is older than the Grenville Orogen and probably represents sediments from a rift basin, and is not considered here further.
- The Sleat Group, exposed on Skye and in Kishorn, where it lies underneath the Torridon Group, with a slight angular unconformity. It is not exposed farther north.
- The Torridon Group, exposed extensively from Kishorn in the south to Cape Wrath in the north.
- The Morar Group occurs above the Moine Thrust, and now part of the Caledonian Orogen. It is the lowest tectonostratigraphic unit of the Moine Supergroup. The Morar Group is now interpreted to be lateral equivalent to the Sleat and Torridon groups, and part of the Grenville Foreland Basin.
- The Loch Eil and Glenfinnan groups, the upper part of the Moine Supergroup, occur in the hangingwall of the Sgurr Beag Thrust. These sequences are younger than *c.* 960Ma (e.g. Cawood *et al.* 2015), and not considered part of the foreland basin. They, too, are not considered here further.

*The Torridon Group**, which forms classic mountains such as Suilven and Liathach, has a total thickness of 5–6km. North of Kishorn, a basal unit, the Diabaig Formation, occurs intermittingly and directly overlies the basement of Lewisian gneiss. The bulk of the Torridon Group is represented by the Applecross and Aultbea formations. The lower *Applecross Formation* is a coarse, gritty, pebbly sandstone with abundant trough cross bedding and channel features (Fig. 4a, *page 26*), as well as dewatering and slumping features. The unit is widely interpreted as a high-energy, fluvial braid-plain deposit with fast deposition by massive, deep and long rivers (Nicholson 1993; Stewart 2002). Going upwards in the stratigraphy, the *Aultbea Formation* is slightly finer sandstone, again with cross-bedding but with near-ubiquitous dewatering and slumping structures: the Aultbea Formation is in essence a 2–3km thick accumulation of quicksand (Fig. 4b). The grain size indicates a medium-energy braid-plain, with fast, sustained deposition. Higher in the stratigraphy, conditions became quieter. The *Cailleach Head Formation*, exposed on the Scoraig Peninsula and Gruinard Island, comprises thinly bedded sandstone with shales and fine sandstone (Fig. 4c), and is interpreted as a fluvio-lacustrine or possibly deltaic environment (Stewart 2002).

* Groups and Formations are in *italics* when first mentioned. — Ed.

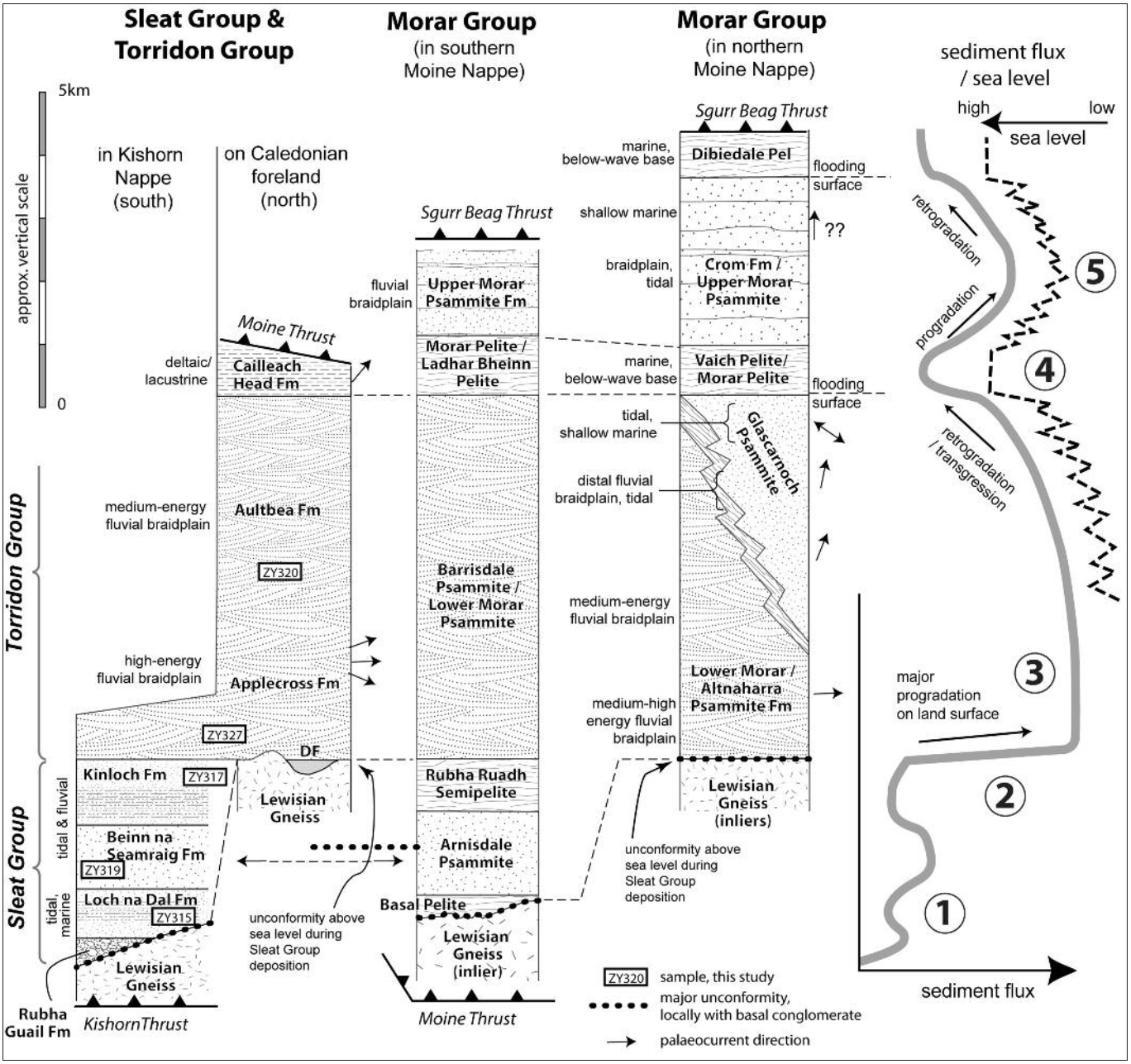


*Figure 3 Stratigraphic framework of the early Neoproterozoic sequences in Northern Highlands. Not shown are the older, Mesoproterozoic (*c. *1180Ma) Stoer Group, and the post-950Ma Glenfinnan and Loch Eil groups, which occur above the Sgurr Beag Thrust (compiled after Ramsay and Spring (1962), Stewart (2002), Bonsor and Prave (2008), Krabbendam* et al. *(2008, 2017), and Bonsor* et al. *(2010, 2012)).*

Overall, the Torridon Group shows a single, 5–6km thick major pulse of sediment, with the coarsest, highest energy deposition by massive, fast-flowing braided rivers in the Applecross Formation, gradually slowing to the lower energy conditions of the Cailleach Head Formation. The paleocurrents were from west to east (Nicholson 1993), so the rivers were bringing sediments from the west.

(see box overleaf.)

The *Sleat Group* occurs stratigraphically below the Torridon, but only occurs in Sleat and Kishorn: north of Kishorn the Sleat Group is absent and the Torridon Group is deposited directly on top of Lewisian Gneiss basement. This means that the Sleat Group must have had some primary boundary to the north. The Sleat Group is a *c.* 3–4km thick sequence of sandstones and shales that has been subdivided into four formations (Stewart 2002):

- *Rubha Guail Formation*, containing conglomerates;
- *Loch na Dal Formation*, dominated by shales and fine sandstone, and interpreted as tidal, shallow marine in origin;
- *Beinn na Seamraig Formation*; mainly structureless, thick-bedded sandstone, but locally with well-developed cross-bedding and slump structures, interpreted as fluvial, braided river deposits; and
- *Kinloch Formation*, shales and fine sandstone commonly with wave ripples and interpreted as tidal and fluvial deposits.

These represent smaller sediment pulses than the Torridon Group (Krabbendam *et al*. 2017).

The Morar Group, east of and above the Moine Thrust (*see* Fig. 1), has been metamorphosed to > 500˚ and is intensely deformed; it is mainly known for its wonderful tectonic structures, including excellent examples of fold overprinting (e.g. Ramsay 1967;

Erosion and deposition in a world without plants

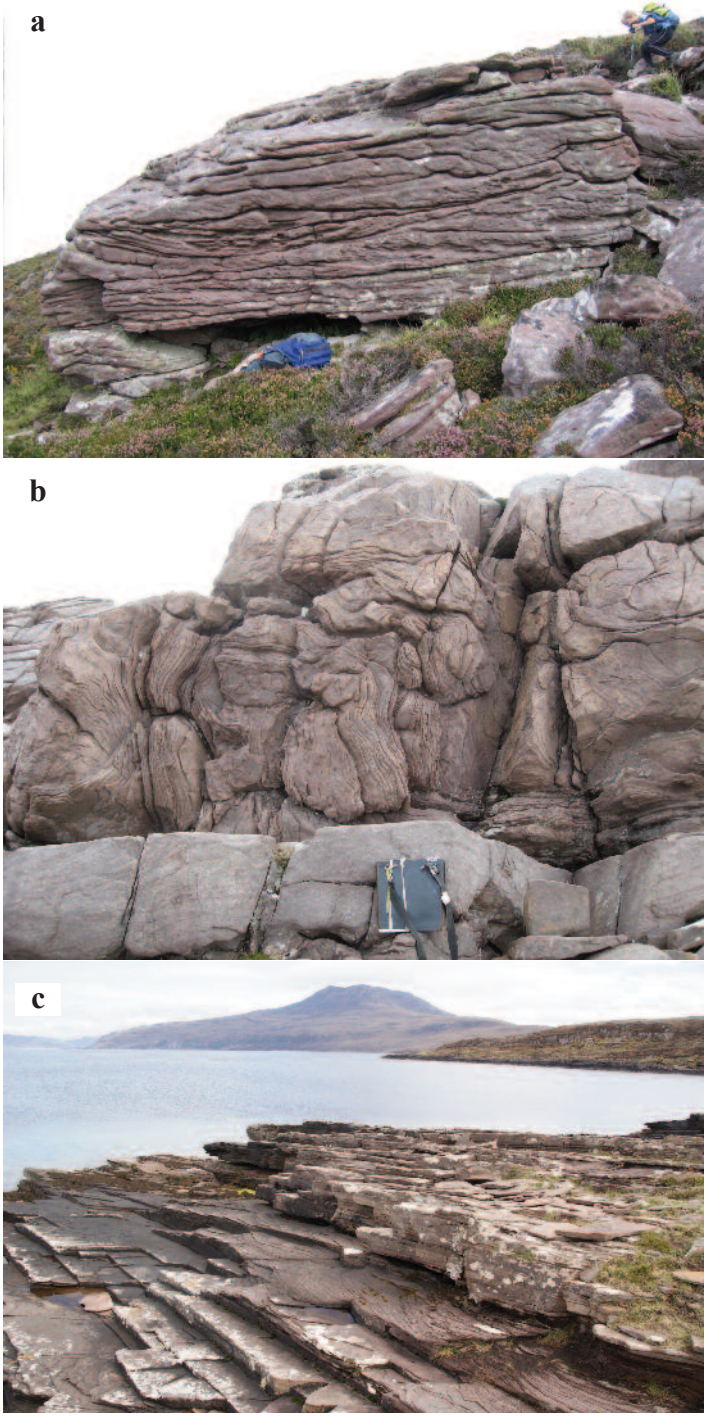
In the Precambrian, Earth was like a different planet because there were no plants on the land surface. There may have been some lichen, but there were no roots, so soil could not have been stabilised by vegetation. Each rainstorm could become a flash flood, loosening and eroding soil material easily, so that erosion rates were likely much higher than today. Moreover, in the modern world, one can get a high water table but no flash floods (for example, in the Netherlands): or you can get flash floods but no high water table (for example, in the Sinai Desert). But in the Precambrian, flash floods could dump metre-thick packages of sand in a matter of hours or days, on top of deposits that were already saturated with water ('quick sand'). It is this combination that likely explains the near ubiquitous occurrence of soft-sediment structures in units like the Aultbea Formation. Furthermore, riverbanks were not stabilised by roots, so could easily collapse, forming slump structures. The lack of roots in instable banks also meant that meandering rivers were rare, so that slow-moving water more likely occurred in some form of distal braided system, with sheet-flooding after rainstorms.

Ramsay and Huber 1987). Thus, for the past 80 years the Morar Group has been a hunting ground for structural geologists, but rather neglected by sedimentologists, mainly because sedimentary structures are typically destroyed by later deformation. Up to about 2000, the Moine as a whole was regarded as dominantly shallow marine in origin (Strachan 1988; Glendinning 1988; Soper *et al.* 1998) — very different from the dominantly fluvial Torridon Group.

While mapping in the central part of the Morar Group outcrop, we noted that sedimentary structures were well preserved in low-strain zones particular in fold hinges, and that sedimentary logging was possible in such domains, but only on south-facing slopes with the least amount of moss and lichen. Using a combination of structural mapping, stratigraphic reconstruction and sedimentology work, a new stratigraphic framework was reconstructed (Bonsor *et al.* 2010, 2012; Krabbendam *et al.* 2014), as summarised in Figure 3. The lowest, most north-westerly unit (the *Altnaharra Formation*) comprises coarse psammite (metasandstone) with pebbly beds with feldspathic clasts, some very clear planar and trough cross-bedding in 1.5–3m thick beds (Fig. 5a, b, *opposite*), and channels with an erosional base (Fig. 5c). Beds are up to 5m thick, and are locally completely slumped (top unit in Fig. 5a). All these features are exactly the same as in the Applecross Formation: the only difference is the subsequent metamorphism, which renders the Morar Group grey instead of red. Thus, the Altnaharra Formation can be correlated across the much later Moine Thrust with the Applecross Formation (Krabbendam *et al.* 2008).

Farther eastwards and upwards, finer grained psammite and semipelite (meta-siltstone) with lower angle cross-beds and fining upwards beds (the *Glascarnoch Formation*); these are interpreted as sheet-flood deposits in a distal fluvial braid-plain, merging into a tidal fluvial shore face (Bonsor *et al.* 2010). In the south the equivalents of the combined Altnaharra and Glascarnoch formations are the Barrisdale Psammite and the Lower Morar Psammite. The psammitic units are capped by the *Vaich Pelite Formation* (or by the Morar Pelite or Morar Schist in the south). It is a massive pelitic schist with big garnets and highly deformed, so that all the sedimentary structures are completely erased and replaced by a dominant schistosity. Nevertheless, the composition shows that the unit was originally clays and silt, deposited under very low energy conditions, and this unit is interpreted as a below-wave-base marine deposit, whereby the widespread occurrence suggests a basin-wide flooding surface (Bonsor *et al.* 2010, 2012). Farther up the succession, psammite returns (*Crom Formation* or the *Upper Morar Formation* in the south) with more slumped cross-bedding, indicating more fluvial deposition.

Figure 4 Torridon Group deposits: (a) metre-scale trough cross-bedding in Applecross Formation; north of Oldshoremore, Sutherland; (b) contorted bedding/soft-sediment deformation in Aultbea Formation, Mellon Udrigle, Aultbea Peninsula; (c) thin-bedded sandstone and shale of the Cailleach Head Formation, Annat Bay, Scoraig Peninsula.



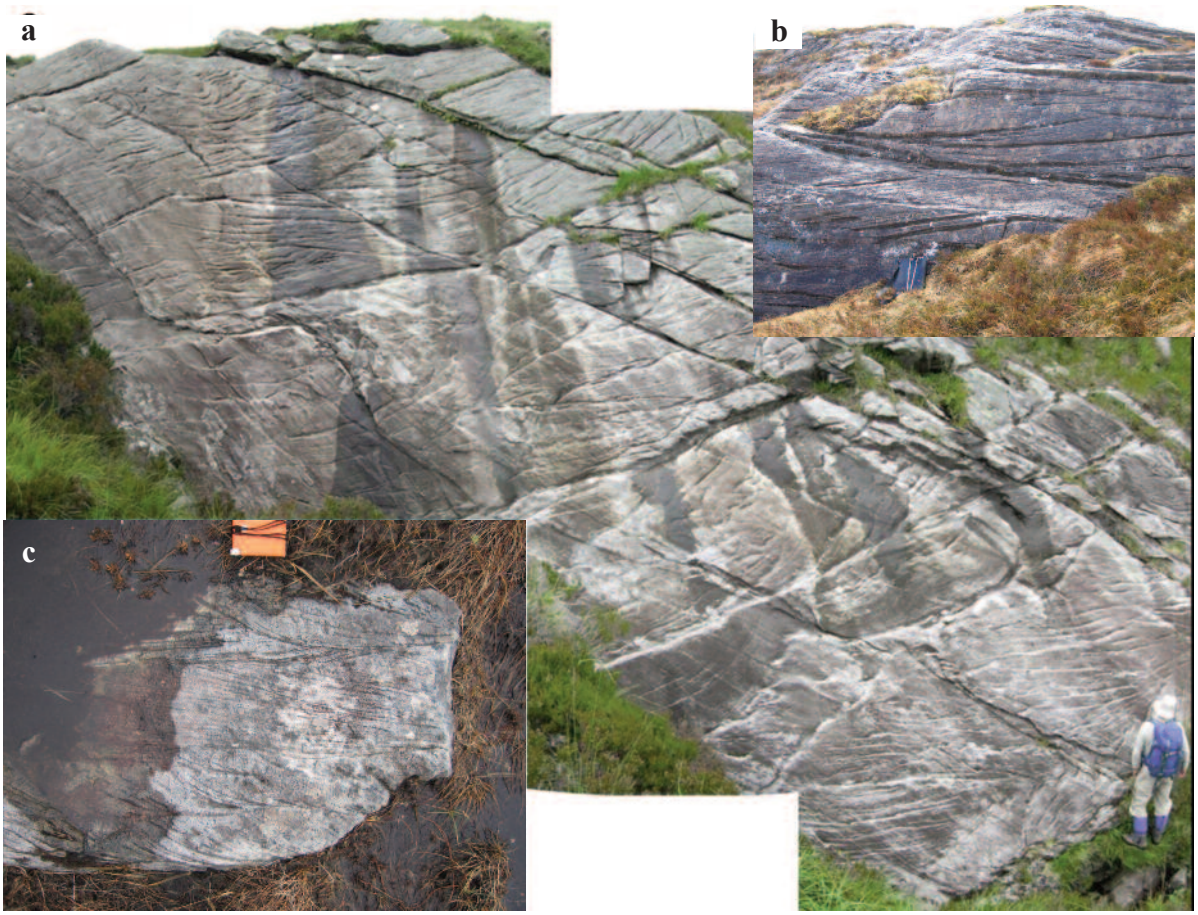


Figure 5 Lower Morar Group (Altnaharra Formation) rocks in Sutherland and Ross-shire: (a) thick-bedded, coarse psammite, with cross-bedding and dewatering pipes at top, Suil a Bhadain Duinn, 3km south of Gobernuisgach Lodge, Sutherland; (b) trough cross-bedded and planar cross-bedded psammite (map case is 300mm high) — sediment transport was NNE to ENE, Carn Mor, 7km WNW of Rosehall, Strath Oykel, Ross-shire; (c) trough cross-beds in medium-grained psammite (compass is 80mm long) — sediment transport was broadly NNE directed, when corrected for tilt, eastern slopes of Beinn an Eo`in, km west of Glen Cassley, Ross-shire.

In summary, there were major high-energy rivers in the Altnaharra Formation, quieter river, sheet-flood to shallow marine deposits in the Glascarnoch Formation, followed by a flooding surface and another pulse of coarser sediment coming in. This is the same pattern that occurred in the Torridon (*see* Fig. 3): there is a large pulse of coarse sediment in the Applecross and the Lower Morar, slightly fining up; then a flooding surface with marine deposition in the Morar Group and lacustrine deposition in the Torridon Group (Cailleach Head Fm), followed by another sediment pulse that is only recorded in the Morar Group.

As noted, the Sleat Group only occurs in the south, whereas farther north the Torridon rests directly on Lewisian gneiss basement. The same feature occurs in the Morar Group: as in Knoydart in the south a number of extra units beneath the major Barrisdale Psammite/Lower Morar were mapped by Ramsay and Spring (1962). These units, the 'Basal Pelite', Arnisdale Psammite and Rubha Ruadh Semipelite are (allowing for subsequent metamorphism) remarkably similar to the units of the Sleat Group (Fig. 6). Again these lower units in the Morar Group only occur in the south, and not in the north. This strengthens the case for correlation between the Torridon/Sleat groups in the west and the Morar Group in the east. It further suggests that the early part of the basin deposition only occurred in the south and was limited to the north, whereas later basin fill (e.g. the Torridon Group and middle-upper Morar Group) propagated over Lewisian gneiss basement to the north (Fig. 7, *overleaf*).

Figure 6 Comparison of Sleat Group and lower Morar Group (meta)sandstone in Lochalsh and Knoydart: (a) fine-grained, thick-bedded sandstone, with poorly developed laminations poorly visible, Bean na Seamraig Fm, Sleat Group, just east of Donald Murchisons Monument, 3km east of Kyle of Lochalsh; (b) fine-grained, buff psammite, thick-bedded with wispy sedimentary laminae, Arnisdale Psammite, lower Morar Group, Aultvoulins, near Inverie, Knoydart Peninsula.

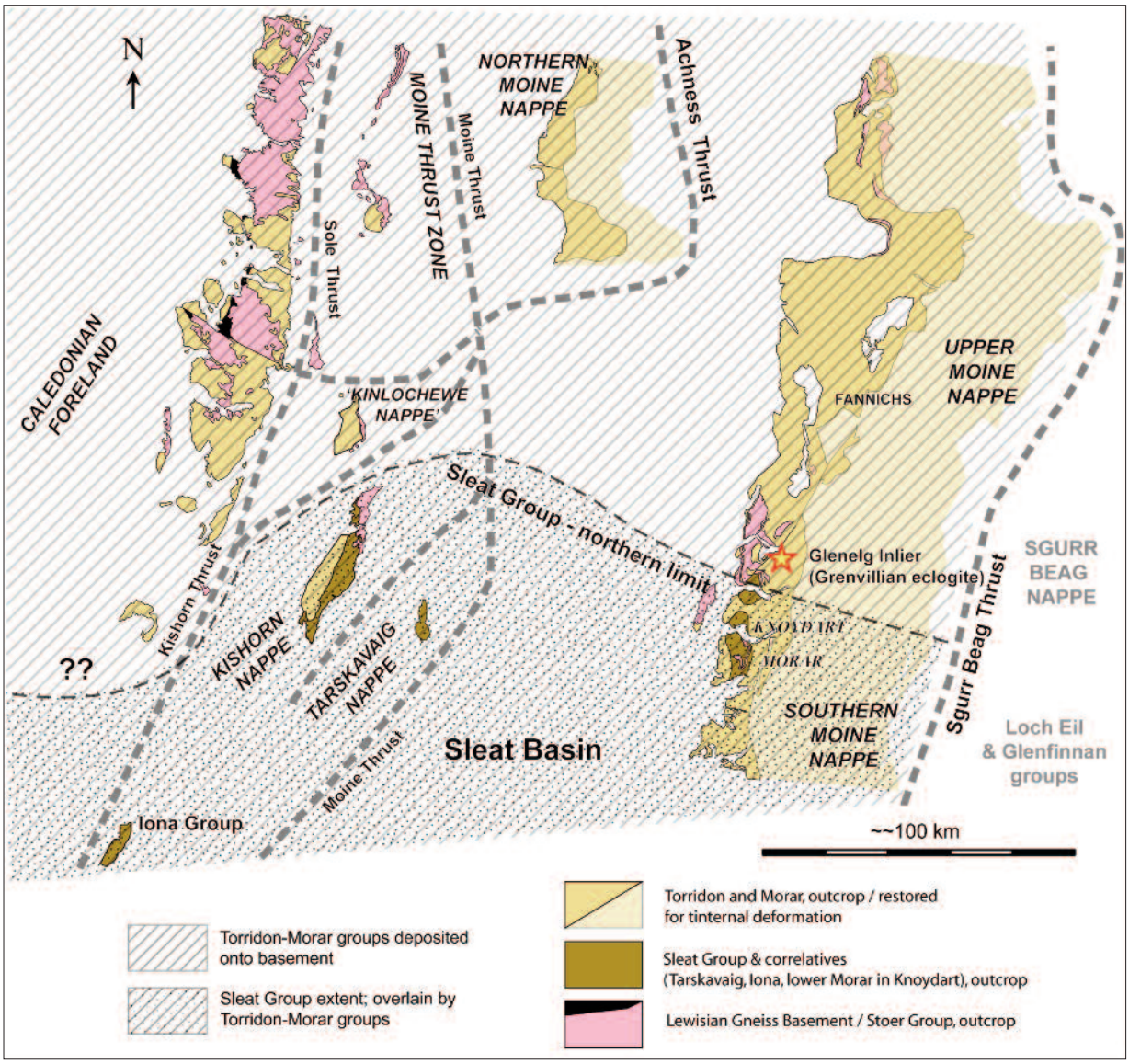


Figure 7 Schematic reconstruction of the Grenville Foreland Basin in the Northern Highlands of Scotland, applying minimum restoration of later Caledonian thrusts. The present-day outcrop and interpreted extent of the Sleat Group and its possible correlatives in Knoydart is shown. The basement north of the Sleat Group basin remained exposed until covered by later Torridon and Morar deposits.

Detrital zircon geochronology

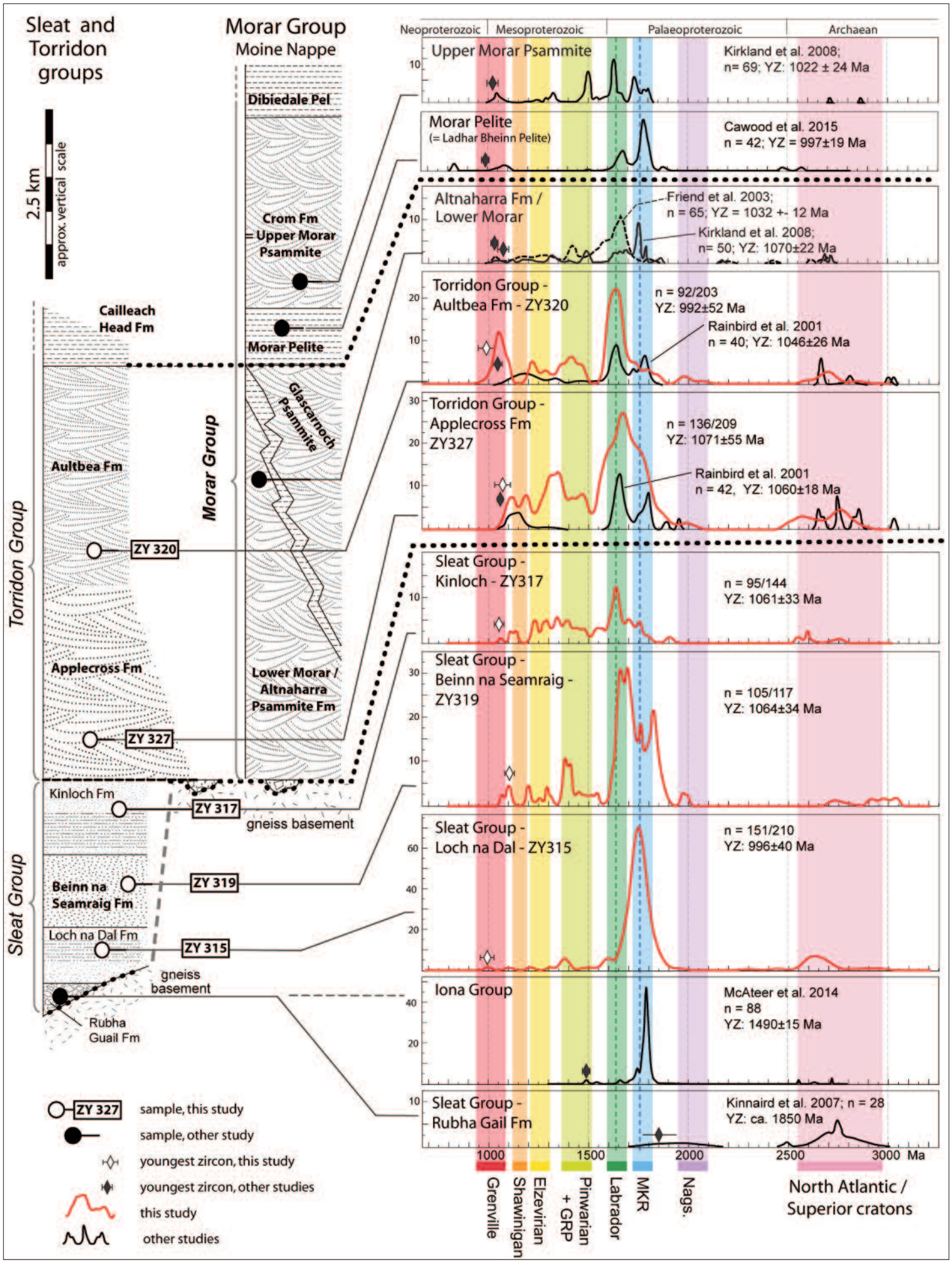
To test the provenance of the (meta)sedimentary rocks, as well as constraining their time of deposition and to test potential correlations, detrital zircon geochronology has been the tool of choice for many years (*see box on page 30*). We analysed a number of samples from the Sleat Group and the Torridon Group (red probability density plots in Fig. 8, *opposite*), and compare these with previously published results (black probability density plots in Fig. 8).

To link sediments to their sources, the detrital zircon ages need to be compared with the protolith ages of the potential source areas. Here, in a reconstruction of the Grenville Orogen and adjacent areas (Fig. 9, *page 30*) the protolith ages are coloured up in the same way as the bars in Figure 8, to enable easy comparison.

The following inferences can be made from the detrital zircon data of the Sleat, Torridon and Morar groups:

- All youngest zircons in our samples are of Grenvillian ages, *c.* 1060–990 Ma, supporting the notion that all units were part of the Grenvillian Foreland Basin.
- The samples contain virtually no zircons older than 2000Ma. Rocks with Archaean or *c.* 2000Ma age in fact make up most of Laurentia (*see* Fig. 2), as exposed in the North Atlantic and Superior cratons, and in Palaeoproterozoic belts such as Nagssugtoqidian Orogen in Greenland and including all of the Lewisian gneiss in Scotland. These areas were thus evidently *not* the main source of the Sleat, Torridon or Morar groups.
- The plot from the Loch na Dal Formation (lower Sleat Group) shows a single major peak of *c.* 1750Ma. Similar age zircons also occur in higher units. These ages correspond with the

Figure 8 (opposite) Detrital zircon age probability density plots, showing absolute frequency against the combined stratigraphy of the Sleat, Torridon and Morar groups (after Krabbendam et al. *2017): (red) and other studies; black (Rainbird* et al. *2001; Friend* et al. *2003; Kinnaird* et al. *2007; Kirkland* et al. *2008; McAteer* et al. *2014; Cawood* et al. *2015); YZ = youngest detrital zircon; GRP = Granite-Rhyolite Province; MKR = Makkovik-Ketilidian-Rhinnian; Nags = Nagssugtoqidian.*


Sleat and Torridon groups
Morar Group
Moine Nappe
2.5 km
approx. vertical scale
Dibiedale Pel
Crom Fm = Upper Morar Psammite
Morar Pelite
Glascarnoch Psammite
Cailleach Head Fm
Aultbea Fm
Applecross Fm
Lower Morar / Altnaharra Psammite Fm
Kinloch Fm
Beinn na Seamraig Fm
Loch na Dal Fm
gneiss basement
Rubha Guail Fm
Torridon Group
Sleat Group
ZY 320
ZY 327
ZY 317
ZY 319
ZY 315
Neoproterozoic
Mesoproterozoic
Palaeoproterozoic
Archaean
Upper Morar Psammite
Kirkland et al. 2008; n= 69; YZ: 1022 ± 24 Ma
Morar Pelite (= Ladhar Bheinn Pelite)
Cawood et al. 2015 n = 42; YZ = 997±19 Ma
Altnaharra Fm / Lower Morar
Friend et al. 2003; n = 65; YZ = 1032 +- 12 Ma
Kirkland et al. 2008; n= 50; YZ: 1070±22 Ma
Torridon Group - Aultbea Fm - ZY320
n = 92/203 YZ: 992±52 Ma
Rainbird et al. 2001 n = 40; YZ: 1046±26 Ma
Torridon Group - Applecross Fm ZY327
n = 136/209 YZ: 1071±55 Ma
Rainbird et al. 2001 n = 42, YZ: 1060±18 Ma
Sleat Group - Kinloch - ZY317
n = 95/144 YZ: 1061±33 Ma
Sleat Group - Beinn na Seamraig - ZY319
n = 105/117 YZ: 1064±34 Ma
Sleat Group - Loch na Dal - ZY315
n = 151/210 YZ: 996±40 Ma
Iona Group
McAteer et al. 2014 n = 88 YZ: 1490±15 Ma
Sleat Group - Rubha Gail Fm
Kinnaird et al. 2007; n = 28 YZ: ca. 1850 Ma
1000
1500
2000
2500
3000 Ma
Grenville
Shawinigan
Elzevirian
Pinwarian + GRP
Labrador
MKR
Nags.
North Atlantic / Superior cratons
ZY 327 sample, this study
sample, other study
youngest zircon, this study
youngest zircon, other studies
this study
other studies

Rhinnian (and Makkovik–Ketilidian) orogens as now exposed intermittingly around the Atlantic. Rocks of *c.* 1750Ma are rare in the Grenville Province in Canada (*see* Fig. 9), but it is very likely they occur (beneath younger rocks) in Ireland and Scotland. The Grenville Orogen is only exposed in two places in Ireland and Scotland: in the Glen Elg inlier in Scotland and the Annagh gneiss in Ireland. Zircon dating gives 1720–1780Ma for their protolith ages. It is thus suggested that the lower Sleat Group was sourced from the Irish-Scottish sector of the Grenville Orogen.

- The Iona Group (as exposed on Iona off Mull, *see* Fig. 1) also has a single dominant 1750Ma peak (McAteer *et al.* 2014), strongly suggesting that the Iona Group is best correlated with the lower Sleat Group (both occur unconformably upon Lewisian gneiss basement). McAteer *et al.* (2014) did not record a youngest zircon of Grenvillian age, but statistically this is not unexpected.
- The Beinn na Seamraig plot shows a similar *c.* 1750Ma peak, but also a separate peak at *c.* 1650Ma. In the Kinloch sample, the 1650Ma peak becomes dominant, and this 1650Ma peak remains dominant in the Applecross and Aultbea formations. It also is the dominant peak in the Altnaharra Formation, sampled in Sutherland (Friend *et al.* 2003) and in the Upper Morar Psammite (Kirkland *et al.* 2008). Rocks of *c.* 1650Ma do not occur in Scotland: instead the most likely source is the massive *c.* 1650Ma Trans-Labrador Batholith, which was uplifted and forms a major component of the eastern Grenville province in Canada (see also Rainbird *et al.* 2001).
- Smaller peaks between 1500Ma and 1200Ma occur in the zircon plots of the Beinn na Seamraig and Kinloch formations and throughout the Torridon Group. Again, rocks of such ages are absent in Scotland, and these zircons are likely derived from terranes within the Grenville Orogen in Canada, such as the Pinwarre and Elzevirian terranes.
- A comparison between the top Sleat unit (Kinloch Fm) with the Applecross Formation, the same peaks occur: a major peak in zircon ages at 1650–1750Ma, some minor peaks 1200–1500Ma, very few zircons older than 2000Ma and all the youngest zircons are of Grenvillian age. Statistically, these are the same distributions. There is thus no difference in source area between the top Sleat Group and the Applecross Formation of the Torridon Group, even though the sedimentology is different.

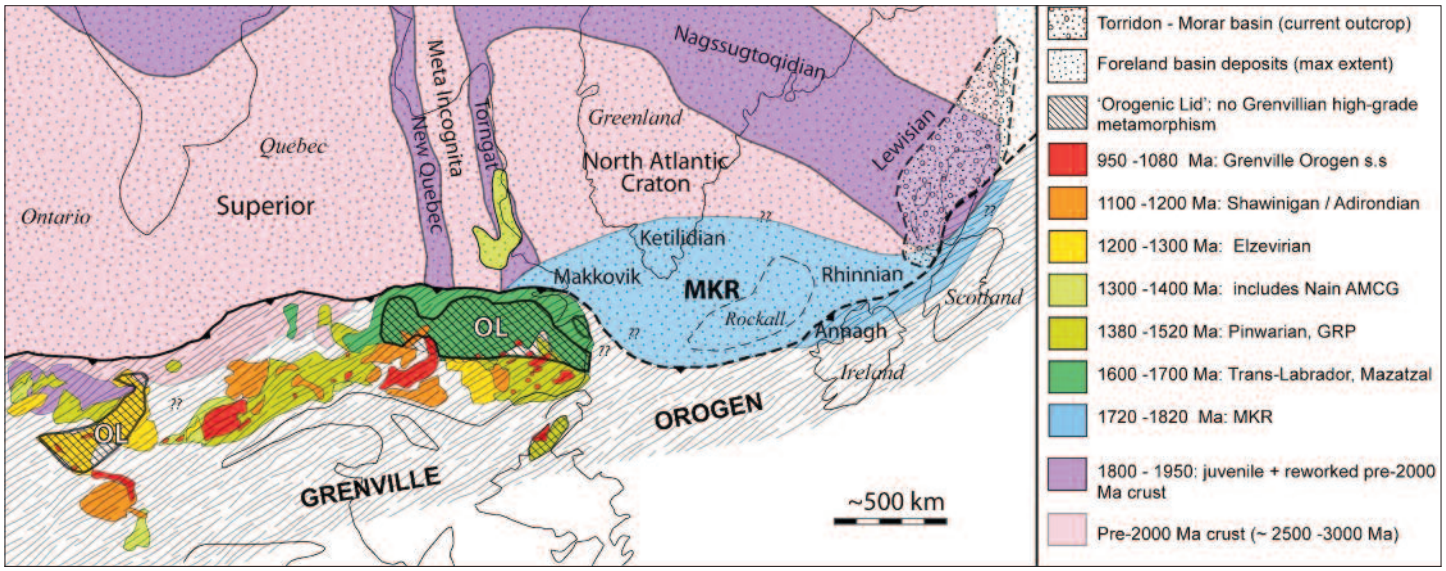
Detrital zircon geochronology

Rocks containing radiogenic elements such as U, Th or K can be dated by measuring the relative amounts of parent and daughter isotopes: for igneous rocks such as granite that means that the date measured is the age of crystallisation. In sedimentary rocks this does not work — and Precambrian rocks have the additional problem that they generally do not contain any fossils suitable for relative age dating. Instead, it is possible to separate out specific detrital minerals such as zircon and rutile that contain a lot of radiogenic elements. Detrital zircon geochronology involves the crushing of a sandstone sample, separating out a number (say 100) of zircon grains and dating these in a mass spectrometer (ICP-MS or SHRIMP). The dates are then plotted in a histogram, which can be smoothed using statistical functions taking care of the analytical error of the individual dates, creating a 'probability density plot'.

Such a probability density plot can tell us several things. Firstly, its shows the youngest detrital zircons, and the deposition of the sandstone, must be younger than the youngest detrital zircon. Secondly, the main peaks in the histogram are representative of the age of the different source rocks, such as a group of granite intrusions in a mountain range from which the sand grains in the sandstone originated. Thirdly, the absence of zircons in a particular age bracket suggests that source rocks with such ages cannot *have been the source.*

- The zircon plots for the Torridon Group can also compared with those in the Morar Group (data from Friend *et al.* 2003; Kirkland *et al*. 2008; Cawood *et al.* 2015). The differences within the Morar Group are greater the overall difference between the Morar and the Torridon groups. Again, in the Morar Group there are very few zircons older than 2000Ma, a large peak in ages *c.* 1650–1750Ma, a smattering of younger peaks and Grenville ages for the youngest zircons.

Figure 9 The Grenville Orogen and its foreland in the North Atlantic region. Crustal protolith ages shown in colour (after Rivers 1997; Rainbird et al. 2001; Gower and Krogh 2002; Park 2005). Within eastern Grenville Orogen only outcropping protolith shown. The inferred extent of the foreland basin deposits is shown by a dot pattern (this study, but see also Rainbird et al. 2012). AMCG = anorthosite-mangerite-charnockite granite; GRP = Granite-Rhyolite Province; MKR = Makkovik, Ketilidian and Rhinnian.



- The Morar Group shows different major peaks. The Alnaharr Psammite in the north shows a major 1650Ma peak (Friend *et al.* 2003), whereas its southern equivalent, the Morar Psammite Formation shows a major 1750Ma peak (Kirkland *et al.* 2008). The Morar Pelite shows a *c.* 1750Ma peak (Cawood *et al.* 2015), whereas the higher Upper Morar Psammite shows a 1650Ma peak (Kirkland *et al.* 2008).

Overall, it appears that the best fit for the source area is either the Irish-Scottish sector of the Grenville Orogen, or the Canadian sector, or a mix thereof, but never the vast cratonic area to north of the Grenville Orogen. There thus seems to source-switching to have occurred: different rivers sourcing from different areas, at different times during the evolution of the basin overall.

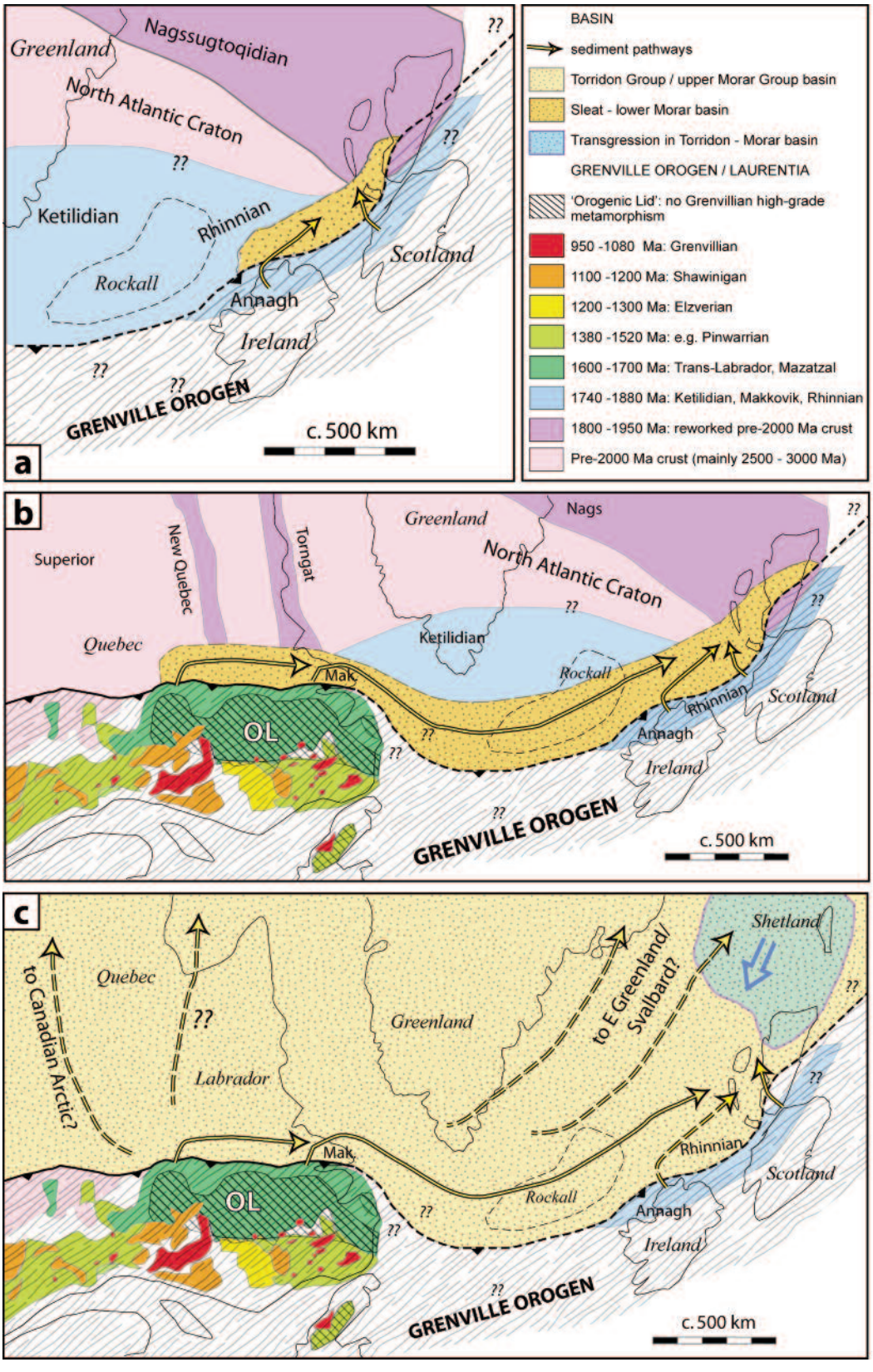
A model for Grenville Foreland Basin evolution

Combining the detrital zircon geochronology with the sedimentology and the overall disposition of the units, a model for the overall evolution of the Grenville Foreland Basin in Scotland can be pieced together (Fig. 10).

The first foreland basin deposits in Scotland (early Sleat Group and likely the Iona Group) occurred in a small, narrow marine basin, limited in extend to the north, possibly with a bounding fault (Fig. 10a). North of this limit the basement remained exposed and little or no deposition occurred. The basin fill is mainly *c.* 1750Ma material, which suggests a relatively local source: Rhinnian-aged rocks that were reworked, uplifted and eroded in the Scottish-Irish sector of the Grenville Orogen.

Within the Sleat Group, and within the same narrow marine/fluvial basin, a shift occurred from 1750Ma detritus to 1650Ma material (Beinn na Seamraig and the Kinloch formations of the Upper Sleat Group). The *c.* 1650Ma material was likely derived from a large granite batholith in Labrador, reworked, uplifted and eroded in the Canadian sector of the Grenville Orogen (Fig. 10b). Thus, a large river system must have developed along the axis of the basin and in front of the orogen, similar to the Ganges course in front of the present-day Himalayas. But some (smaller)

Figure 10 Suggested evolution of eastern Grenville Foreland Basin: (a) Grenvillian foreland basin in early Sleat times, mainly sourced from the Irish-Scottish sector of the Grenville Orogen; (b) Grenvillian Foreland basin in mid to late Sleat times: change to sources in the eastern Grenville Province. (c) Grenvillian foreland Basin in Torridon-Morar times. Pathway to Canadian Arctic after Rainbird et al. *(1997, 2012). Blue areas and open blue arrow north of Scotland indicate possible origin of marine transgression in the upper Morar Group.*

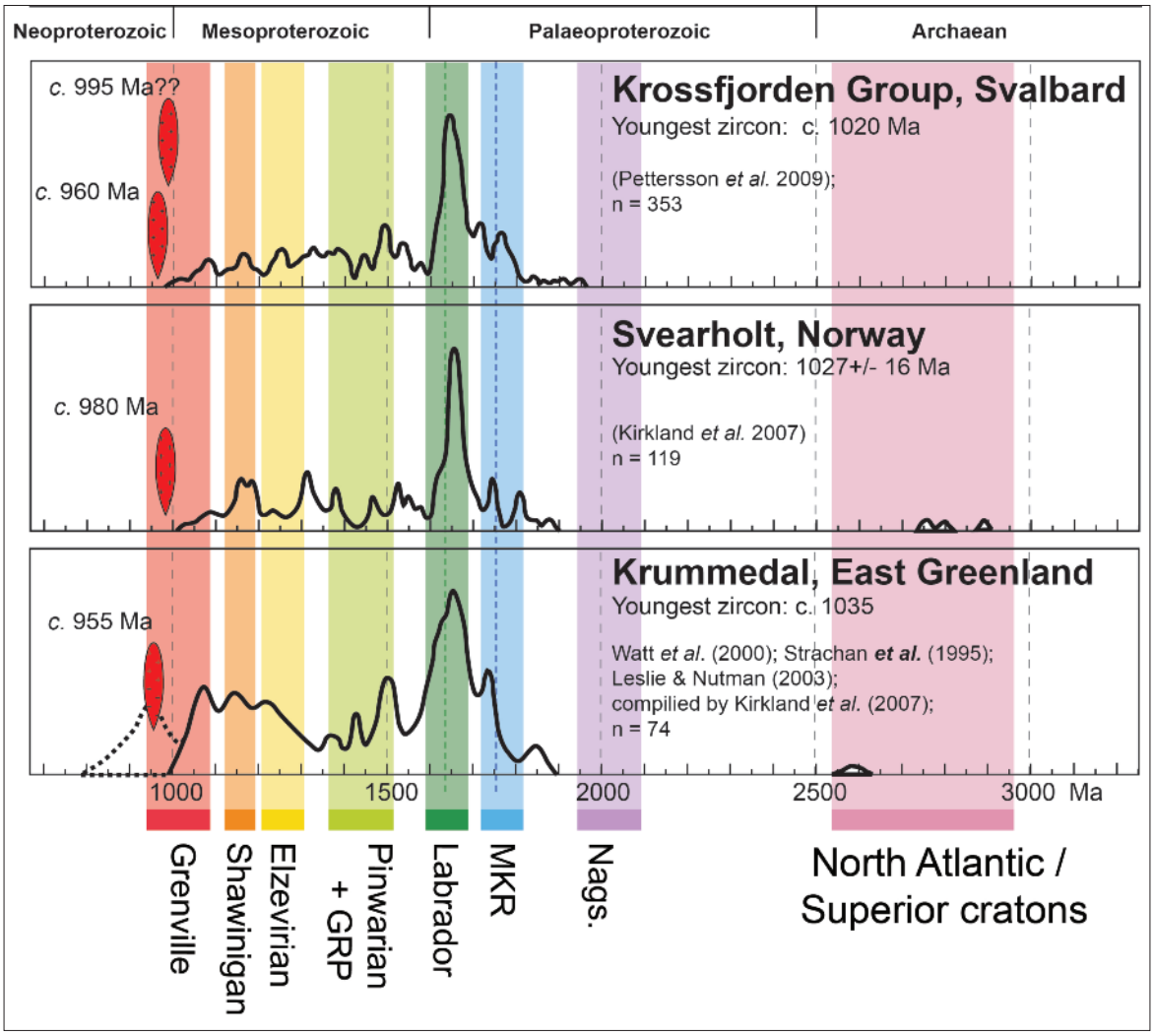


rivers still transported *c.* 1750Ma originating from the Scottish-Irish sector of the Grenville Orogen.

Then a major change in basin dynamics occurred (Fig. 10c). The basal units of the Torridon and Morar groups heralded the arrival of a system of massive, fast-flowing rivers that deposited large amounts of sediment in a short time. The smaller basin 'overspilled' and areas that were previously exposed then became buried beneath thick sandstone units (Fig. 10c). This massive pulse of detritus originated mainly from the Canadian sector of the Grenville Orogen, with a small component still from the Irish-Scottish sector of the orogen. After some 5–6km of sand was deposited, things calmed down somewhat. The basin subsided, base level dropped, and a transgression occurred: a flooding event from a sea, likely located to the north or north-east. In the Morar Group this relative pause in sedimentation event is represented by the marine Vaich Pelite/Morar Pelite units; in the Torridon Group it is represented by the low-energy marine or lacustrine Cailleach Head Formation. The rivers coming from the Canadian sector would have ceased to flow — or lost their power — and it appears that the Morar Pelite was mainly sourced from the Irish-Scottish sector of the orogen. However, a further pulse of fluvial deposition occurred, depositing a further 2–3km thick package of sand (Crom Psammite/Upper Morar Psammite), which appears to have come from the Canadian sector of the orogen.

Overall, the Torridon and Morar groups appear to be the proximal part of a massive, continent-wide foreland basin. Can this pulse of deposition be linked to the more distal deposits (*see* Fig. 2), farther afield? Deposits with detritus from the Grenville Orogen have been found on islands in the Canadian Arctic; big rivers must thus have crossed the entire continent of Laurentia (Rainbird *et al.* 1997, 2012). In the North Atlantic, distal deposits occur in Greenland (Krummedal sequence), in Norway (the Svaerholt sequence) and on Svalbard (the Krossfjorden sequence). The detrital zircon data of these units (Fig. 11) show few or no zircons older than 2000Ma, a dominant 1650Ma peak, a smattering of zircons between 1600Ma and 1200Ma, and youngest zircons all of Grenville age, *c.* 1020Ma (data mainly from Kirkland *et al.* 2007; Petterson *et al.* 2009). The main elements of the detrital zircon signature are thus exactly the same as in the Torridon Group and in the Altnaharra Formation, suggesting that the major Torridon-Morar pulse of deposition propagated all the way to these distal basins. In addition, these distal deposits in Greenland, Svalbard and Norway are intruded by 960–920Ma granites, related to a later, separate Valahalla (or Renlandian) Orogeny (Cawood *et al.* 2010). Similar ages of intrusion or high-grade metamorphism have recently been documented in the Morar Group and equivalent units in Shetland and the Northern Highlands (Cutts *et al.* 2009; Bird *et al.* 2018).

Figure 11 Detrital zircon age probability density plots for Neoproterozoic sequence in Svalbard, Norway and East Greenland (after Kirkland et al. *2007; and references therein); Petterson* et al. *2009. GRP = Granite-Rhyolite Province; MKR = Makkovik-Ketilidian-Rhinnian; Nags = Nagssugtoqidian.*



Thus, the major pulse of deposition represented by the Torridon, Morar and more distal units happened between *c.* 1050–1000Ma (age of youngest zircons) and *c.* 960–920 Ma, when the units where reworked in a separate Renlandian Orogeny. This time-frame coincides with the late Ottawan to Rigolet phases of the Grenville Orogeny (Rivers *et al.* 2012), confirming the case for synorogenic deposition of the proximal units in a foreland basin, and the distal units in further basins.

Conclusions

Detrital zircon geochronology in combination with sedimentology and stratigraphic considerations shows that the Sleat, Torridon and Morar groups were sourced from the Grenville Orogen. The deposition was synorogenic: part of the Grenville Foreland Basin is thus preserved in northern Scotland, although much of this once massive basin has now disappeared. Different phases of deposition in the Grenville Foreland Basin can be distinguished. The Sleat and Iona groups represent an early phase of deposition in a narrow, partly marine foreland basin. The Torridon-Morar groups were deposited by a massive river system running parallel to the orogenic front, but likely linked to more distal deposits in east Greenland, Svalbard and Norway. This deposition must have represented a massive erosive phase of the Grenville Orogen.

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Evolution of life on land: how new Scottish fossils are re-writing our understanding of this important transition

Dr Tim Kearsey

BGS Edinburgh

Romer's gap — a hole in our understanding

It has long been understood that at some point in the evolution of vertebrates there was a transition point where they moved from mainly subsiding in water to living on land. However, until recently there had been no fossil evidence that documented how vertebrate life stepped from water to land. This significant hole in scientific knowledge of evolution is referred to as Romer's gap after the American palaeontologist Alfred Romer, and it has been challenging palaeontologists for generations. However, after years of searching, the answers have begun to be unearthed. Recent discoveries from the borders of Scotland are finally filling in the last piece of this story.

What do we know about the origin of life on land?

For many years our understanding of how and why vertebrates came on land was limited by a lack of fossils. The limbed fish, *Eusthenopteron*, discovered in 1881, has been for much of the 19th and 20th century our only example from the time of the transition. However, new research has shown this is completely aquatic (Laurin *et al.* 2007) — It's about as terrestrial as a salmon!

In the last 30 years our understanding has improved dramatically. Discoveries from Devonian rocks of Greenland and Arctic Canada of limbed tetrapods such as *Acantostega* and *Ichthyostega*, discovered by Jenny Clack and Per Ahlberg, and *Tiktaallik*, discovered Neil Shubin and colleagues, have shed light into this transition. These fossils have proto-limbs, some with up to eight fingers; however, they couldn't support their bodyweight on land and still had functioning gills (Clack 2012).

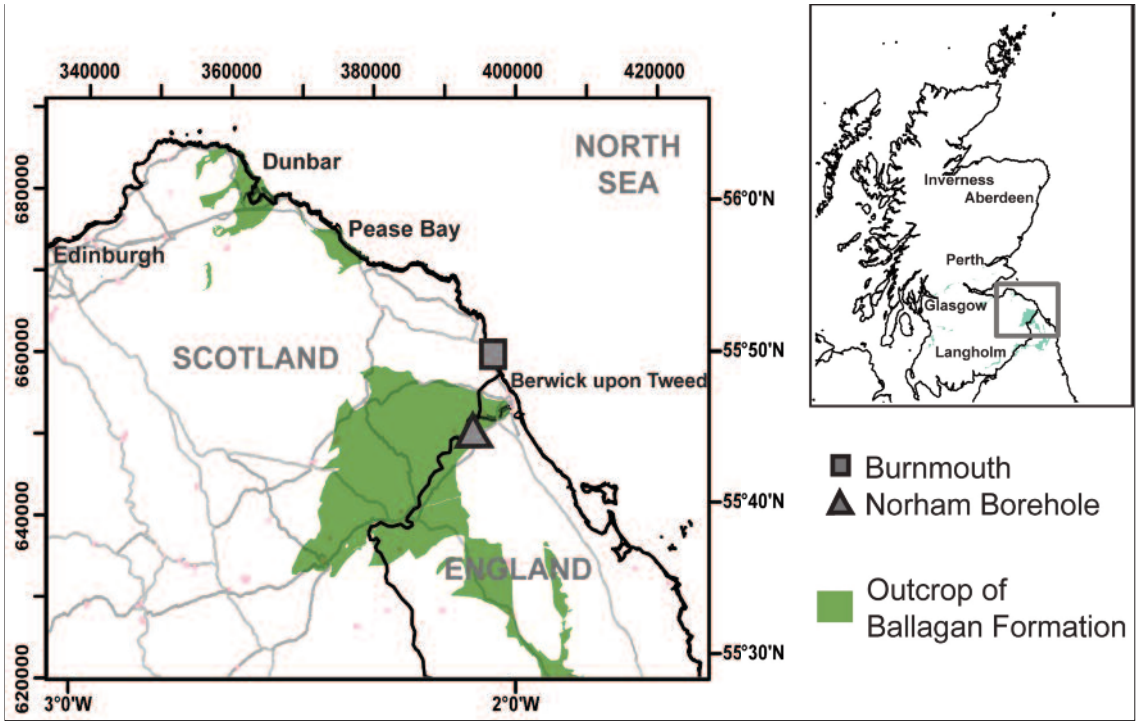
Meanwhile at a quarry called East Kirkton Quarry near Edinburgh in Scotland vertebrate fossils were discovered that are 10 million years younger than the Greenland fossils. These include *Westlothiana*, which is thought to be the first amniote (egg-layer) or possibly early reptile (Smithson and Rolfe 1990) and *Balanerpeton* an extinct genus of temnospondyl amphibian. These fossils show that 10 million years after *Acantostega* and *Ichthyostega* evolved, vertebrates were completely terrestrial and had started to diverge into the separate groups that make up modern terrestrial vertebrates.

Nevertheless, the actual moment of the transition from dominantly aquatic to dominantly terrestrial life styles still remained elusive, with no fossil evidence to show this transition. So much so that it gained the name Romer's gap. This period of the Tournasian, which is the base of the Carboniferous, does not yield fossils and comes directly after the mass extinction at the end of the Devonian.

Evolution of the landscape

At the same time as vertebrates were making the transition from the water onto land, the landscape itself was going through one of the most dramatic changes in the history of the planet. A literature review study conducted in 2012 by Neil Davis and Martin Gibling (Gibling and Davies 2012) has revealed that before the Devonian period fluvial systems were braided and there were no meandering fluvial systems. Anabranching-anastomising rivers were first recognised in sedimentary deposits relating to the Carboniferous age.

Figure 1 Location map showing main tetrapod sites. Green area is from the British Geological Survey DiGMapGB (© NERC 2018). It contains Ordnance Survey data (© Crown copyright and database right 2018.)



The complexity of fluvial systems is linked to the evolution of vegetation and in particular to trees. In order to form floodplains, there needs to be deep-rooted vegetation that can stabilise the banks and flood plains of the fluvial system. Trees evolved on coastal plains, while the interior of the continents was still mostly un-vegetated. Through the Devonian and into the Carboniferous trees advanced farther inland, initially using the rivers as pathways into the uplands. This also had an effect on the rivers themselves, causing them to slow down and enabling wetlands and marshes to form.

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This change may have provided environments that made it possible for vertebrates to come onto land, but without the fossils from Romer's gap it is impossible to prove this link.

Finding Fossils in Romer's gap

The rocks found around the Borders of Scotand and England are of Tournaisian age, the age of Romer's gap. These rocks are in the Ballagan Formation, previously called the Cementstone Formation, which outcrops all the way around the edges of the Midland Valley of Scotland, and on the northern edge of the Northumberland Basin (Fig. 1, *previous page*). A professional fossil collector, the late Stan Wood, and Cambridge University researcher, Tim Smithson, had a hunch; in the Ballagan Formation and elsewhere in the world where fossil fish had been found, tetrapod fossils have also been found. Therefore they surmised that there could potentially be other undiscovered tretrapod fossils in the Ballagan Formation. After ten years of searching all the outcrops of the Ballagan Formation in England and Scotland they finally found tetrapod fossils (Smithson *et al*. 2012).

Based on these tantalising discoveries, a five-year, multi institution research project was started named Tetrapod World: early evolution and diversification (TW:eed). This brought together palaeontologists, sedimentologists, palynotogists and palaeoclimatolgists from the National Museum of Scotland, the universities of Leicester, Cambridge and Southampton, and the British Geological Survey. Our goal was to fully investigate the fossil sites to discover as many tetrapods as we could, as well as to try to understand the ecosystem, climate and landscape that these animals were living on, to understand what was happening during Romer's gap.

The team focused on several sites in the Borders of Scotland, principle among them is the coastal section at Burnmouth where the entirety of the Ballagan Formation is exposed. Inland the project looked at all the known exposures of the Ballagan Formation, and on the River Whiteadder the river channel was restricted to expose the river bed where Stan Wood had found some of the most complete tetrapod fossils (Fig. 2). Also, a 500m borehole was drilled near Berwick-upon-Tweed to core the entire succession to create a high-resolution chronology and palaeoclimate record next to which the fossils could be plotted.

Tetrapod discoveries

Five new tetrapods were found *Perittodus apsconditus*, *Koilops herma*, *Ossirarus kierani*, *Diploradus austiumensis* and *Aytonerpeton microps* (Clack *et al.* 2017). All of the fossils came from relatively small creatures — the largest skull was only *c.* 80mm long (Fig. 3, *opposite*). The smallest was *Aytonerpeton microps*, knicknamed 'tiny', which had a skull of 10mm and was found by 'accident' by a Masters student at Cambridge University, Ben Otto, who had been given the task of CT-scanning a small piece of rock that was thought to contain some fish bones in it, but he was surprised to find most of the skeleton of a tetrapod in it! (Fig. 4, *opposite*)

Phylogenetic analysis of the new tetrapods suggested that three of the taxa were stem tetrapods: meaning they are not part of either amniotes or amphibians. These all showed features associated with Devonian and Carboniferous tetrapods, suggesting that they were diversifying. The other two tetrapods had features associated with stem amphibians, suggesting that the amphibians had already started to become a separate group at the beginning of the Carboniferous (Clack *et al.* 2017).

Other fossils and the ecosystem

The tetrapods were not the only fossils that were found (Fig. 5, *page 38*). There were many fossils of lungfish, similar to lungfish living today. There were also examples of Actinopterygian fishes and other types of bony fish, as well as *Gyracanthus*, a extinct type of bottom feeding shark. There are examples of stranger animals, too. We have fossils of Eurypterids, often informally called sea scorpions; and on land we have evidence of Myriapods (centipedes). Some of them are thought to be more than one

Figure 2
TW:eed Project fieldwork in the Borders of Scotland.

meter long, and probably bigger than the tetrapods. However, these are not likely to be the top predators in this ecosystem; that is likely to be a Rhizodont. These are large eel-like fish with sharp fang-like teeth. The biggest Rhizodonts we found associated with the tetrapods was 1m long, but elsewhere, at this time some have been found that are as big as 7m in length.

Figure 3 The Fossil remains of 'Ribbo' the biggest tetrapod found in the Ballagan Formation (British Geological Survey image).

Landscape and climate

To put the fossils in their context and understand what might have been driving their evolution, the sediments and palaeoclimate were also studied. In the Tournasian the UK was at tropical latitudes, and the Borders of Scotland were a low-lying wetland that stretched through the Midland Valley of Scotland and out into the North Sea. To the south of the Southern Uplands was a shallow sea, which went as far west as Belfast harbour and was connected to a range of shallow, tropical seaways that continued to Nova Scotia in Canada. The Atlantic had not opened yet.

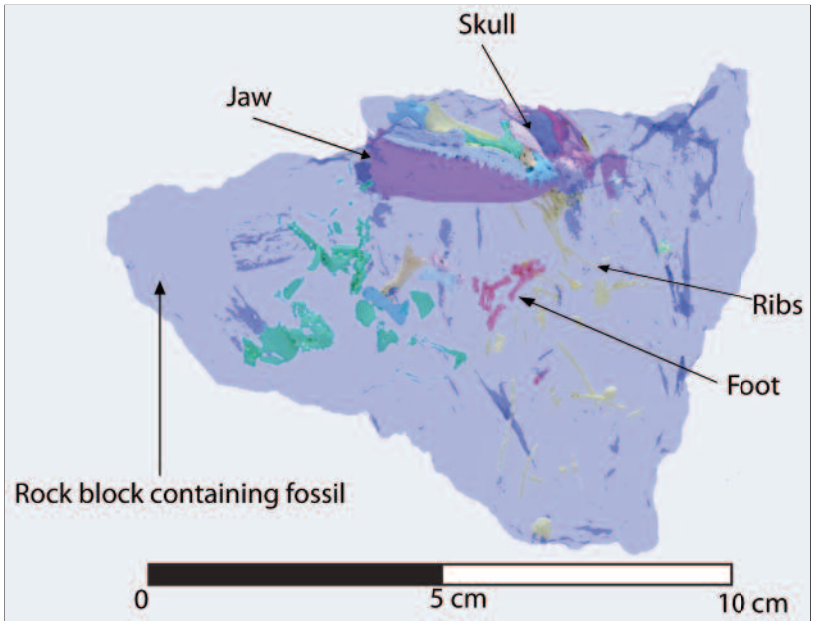
The sediments of the Ballagan Formation are dominated by siltstones that were deposited in shallow lakes and by floods. Many of these siltstones were then altered by root action and soil processes to form palaeosols. There are also beds of sandstone that show trough cross-bedding fading up into trough cross-ripples, with laminated tops on top of which sit abandoned facies with palaeosols (Bennett *et al.* 2016). These represent sinuous fluvial channels forming on a low-lying floodplain. There are also thin beds of dolomicrite and evaporates, which formed in saline alkaline lakes — open lakes with a marine connection (Bennett *et al.* 2016).

The section has a large diversity of root traces, from small plug roots to the occasional root of Lycopod trees. Many of these root traces are preserved as carbon films, suggesting that they were growing in permanently waterlogged conditions. Some of the palaeosols are reddened and contain desiccation cracks, suggesting that some areas were not waterlogged. All this evidence points towards a landscape that was similar to the modern everglades (Fig. 6, *overleaf*).

Using the geochemistry of the palaeosols it is possible to estimate the mean annual rainfall that fell on the floodplain. These give an estimate of 1,000mm to 1,500mm of rain per year, which, given the tropical latitude of Scotland in the Carboniferous, suggests there was a monsoonal climate. This conclusion is also supported by the occurrence of evaporites and desiccation cracks (Kearsey *et al*. 2016).

The tetrapods fossils themselves were found associated with flood deposits overlying the palaeosol. The degree of articulation of the bones suggests they had not moved far, indicating that they lived on the land surface rather than in the rivers and lakes.

Figure 4 Fossil remains of Aytonerpeton microps *discovered through CT scanning.*



Why did vertebrates come on to land?

The new discoveries from Scotland and Northumberland have shown that 'Romer's gap' is a collection bias, and we now have fossils that appear both to show Devonian and Carboniferous characteristics. If this was the moment that our ancestors spent more time on land than in the water, then we need to ask, 'What is the reason this happened?' Almost certainly there was not just a single factor at work. The increase in diversification of fluvial systems from braided to meandering from the Devonian Period and after created new environments that could be exploited by tetrapods. The highly seasonal climate seen in the Ballagan Formation would have favoured creatures that could survive both in water and on land, especially as lakes and pools became evaporate and more saline. Finally, the presence of large predators in rivers and potential prey on land also added to the evolutionary pressures.

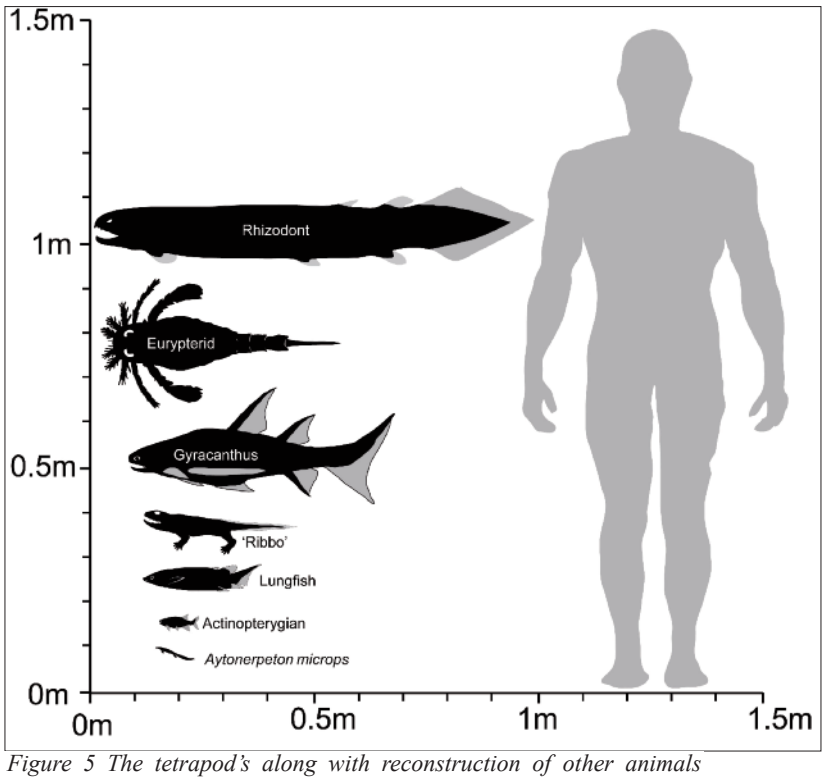


Figure 5 The tetrapod's along with reconstruction of other animals found in the Ballagan Formation with a human for scale.

Overall, the TW:eed project has started to fill a significant gap in scientific knowledge and put the Borders of Scotland at the heart of our understanding of the evolution of life on land.

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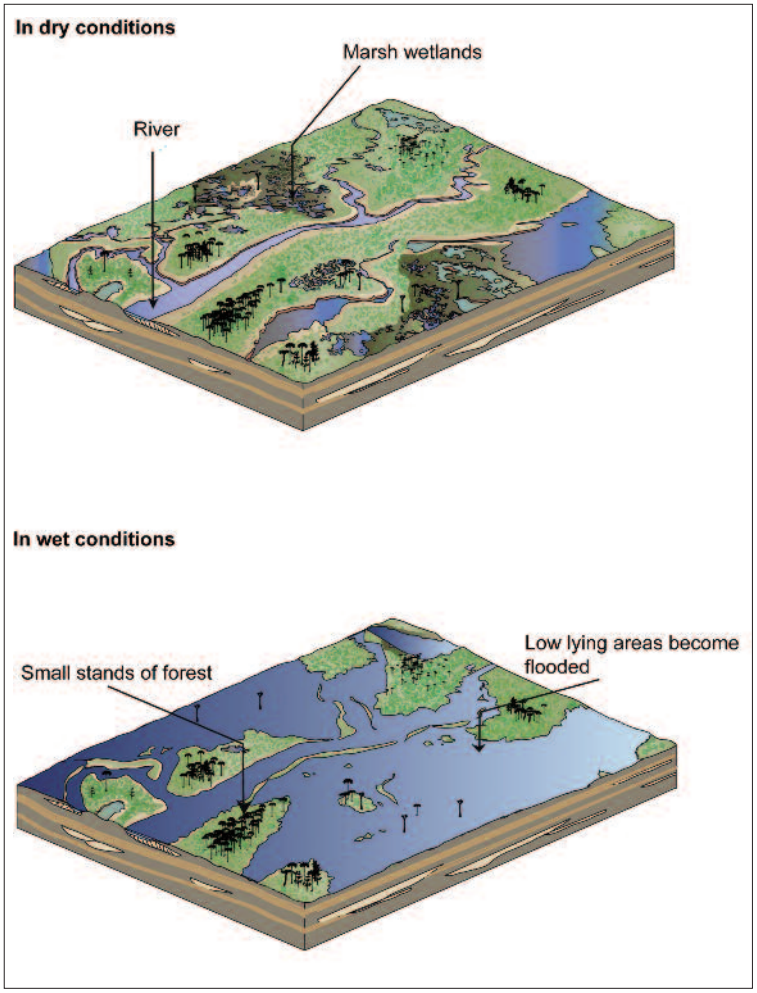
Figure 6 Reconstruction of the environment the tetrapods were living in the dry and wet season.



Building the Queensferry Crossing: aspects of engineering geology

Paul Mellon

(Geotechnical Manager, Transport Scotland, Glasgow)

Abstract

The Queensferry Crossing is a major new road bridge across the Firth of Forth, whose foundations presented significant challenges of engineering geology. The paper describes the process leading to the successful completion of the foundations: from the initial site investigations; through the development and design of foundation solutions; to foundation construction. Key challenges arising are identified, together with the approaches adopted to overcome them.

Figure 1 The Queensferry Crossing (left), Forth Road Bridge (centre) and Forth Bridge (right,) looking north.

Introduction

The Queensferry Crossing, opened to traffic at the end of August 2017, is a new 2.7km-long crossing of the Firth of Forth, connecting Edinburgh with the north. It has been the largest civil engineering project in Scotland for a generation, and the completed bridge will stand beside the existing Forth Road Bridge and Forth Bridge (rail) in a unique display of bridge engineering from three consecutive centuries (Fig. 1).

This paper describes the process necessary to realise a civil engineering project of this scale from the viewpoint of engineering geology, with illustrations of the role of Engineering Geologists and of particular geotechnical aspects of note.

Background

Queensferry has been a strategic crossing point of the Firth of Forth linking Edinburgh and the north for 1,000 years. Ferries were supplemented by the first fixed (railway) crossing, the celebrated Forth Bridge, in 1890, with the last boats being replaced by the Forth Road Bridge in 1964. Traffic volumes and maximum vehicle weights on the Forth Road Bridge have increased significantly since then. Inspections from 2004 onwards disclosed deterioration of the suspension cables, which, if continued, could compromise the capability of the bridge. As a consequence, the Scottish Government initiated studies into a potential replacement crossing through the Scottish national transport agency, Transport Scotland.

A number of options including bridges and tunnels at different locations across the Firth of Forth were considered, but the preferred option was a new cable-stayed bridge immediately upstream of the existing bridges. Specialised works have arrested further deterioration of the cables on the existing Forth Road Bridge, but it cannot be guaranteed to continue to provide the necessary level of service into the future without sustained and significant disruption for repairs. Consequently, the Scottish Government decided to proceed with the new crossing to secure the continued capacity and reliability of this strategic transport link.

The proposed scheme

The new crossing comprises a three-towered cable-stayed bridge, spanning the two principal shipping channels at this location on the Forth, which are separated by a rocky tidal islet suitable for accommodating the central tower (Fig. 2, *overleaf*). The main bridge is approached by viaducts supported on V-shaped piers. The overall length is 2.7km and the two main spans are 650m each. The three towers are more than 200m high, making it the tallest bridge in the UK. Including abutments, the crossing has

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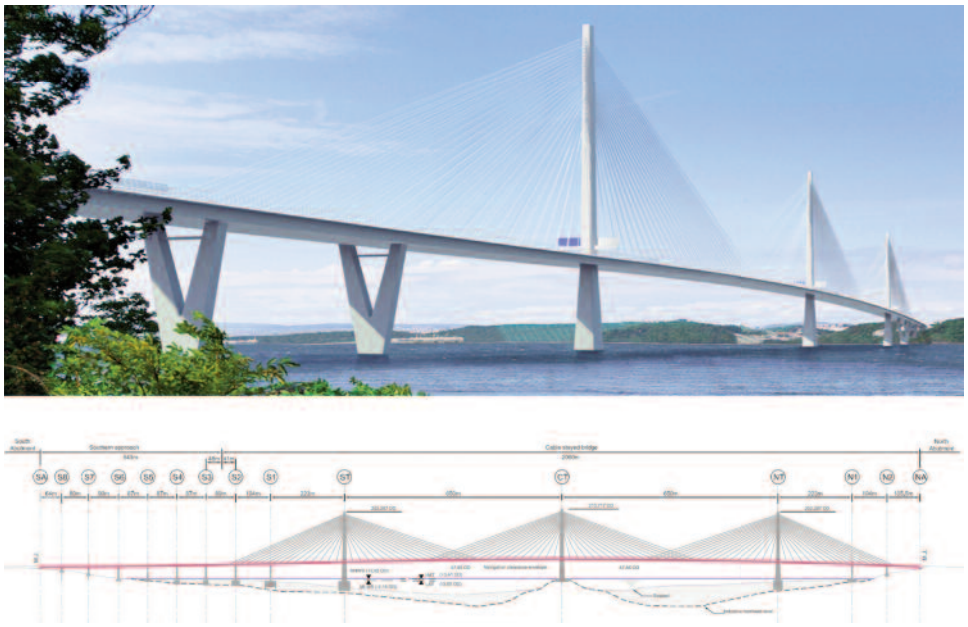


Figure 2 The Queensferry Crossing: top, computer rendition; bottom, elevation.

15 foundations, two of which are tidal and eight are fully underwater. On land, new connecting roads and improvements to the existing road network extend north and south over a total distance of 22km.

Physical and geological setting

The Firth of Forth is the drowned estuary of the River Forth and the narrows at Queensferry separate the more truly estuarine inner Firth from the dominantly marine outer Firth (Fig. 3). Conditions at the crossing location are tide-dominated. Water depth ranges up to *c*. 40m in the channels, although construction took place in water depths limited to 20m. The tidal range is 5m and tidal currents of about 5m/s can occur, with significant effects on construction activities. The dominant westerly winds and seasonal easterlies can have a significant effect on activities above water level, but wave heights are generally under 0.5m due to the short fetch.

The solid geology comprises sedimentary rocks of Lower Carboniferous (Visean) age, consisting of dominantly sandstone/siltstone/mudstone shallow marine/lagoonal/deltaic/fluvial sequences of the approximately coeval Sandy Craig Formation (north shore) and West Lothian Oil Shale Formation (south shore — specifically the Calders and Hopetoun Members). Some of the thicker sandstones are named, having been quarried on land as building stones — notably the Dunnet Sandstone (Hopetoun Member) and the Port Neuk Sandstone (Sandy Craig Fm). Coals occur frequently to the north and oil shales to the south, but while former mine-workings affect the connecting roads, no mining extends beneath the Forth at this location. Tuffs occur sporadically (including the named Port Edgar Ash in the Hopetoun Member and a rather thicker but un-named one in the Sandy Craig Fm).

The one significant limestone, the Burdiehouse Limestone, is a distinctive lagoonal limestone of regional significance as a marker horizon, forming the base of the Hopetoun Member.

These sedimentary rocks have been intruded by both the major suites of late-Carboniferous dolerite sills that occur in the Midland Valley. A sill from the alkali-dolerite suite forms the raised-beach cliff at the southern landfall of the crossing, while thick sills of the quartz-dolerite suite form the headland on the north shore, which narrows the Firth at this point as well as the tidal islets in the middle of the narrows.

A feature of these intrusions is the presence of highly altered dolerite, *known* locally as 'White Trap' (Fig. 4, *opposite*). As suggested by the name, it is pale in colour (usually creamy-white) and consists of an aggregate of clay and carbonate minerals, sometimes pseudomorphing recognisable igneous textures. The principal modes of occurrence are as completely altered thin sills (<1m thick) or as bands or veins (<1m thick) in larger unaltered dolerite bodies. It is surmised that the alteration took place simultaneously with intrusion in the presence of volatiles (particularly water and carbon) contributed by the host sedimentary rocks or as metasomatism by late-stage hydrothermal fluids.

The strata have been gently folded (dips generally less than 20˚), and faulted with a dominant E–W trend parallelling and possibly controlling the orientation of the Firth.

No evidence is present of the intervening geological history until the Quaternary, unless some of the deeper weathering in the dolerite sills can be ascribed to Tertiary processes.

In the Pleistocene, a pre-existing E–W trending valley was overdeepened by eastward ice movements and the subsequent deglaciation; rockhead can be up to *c.* 80m below sea level in the vicinity. At the crossing location, the main channel bifurcates

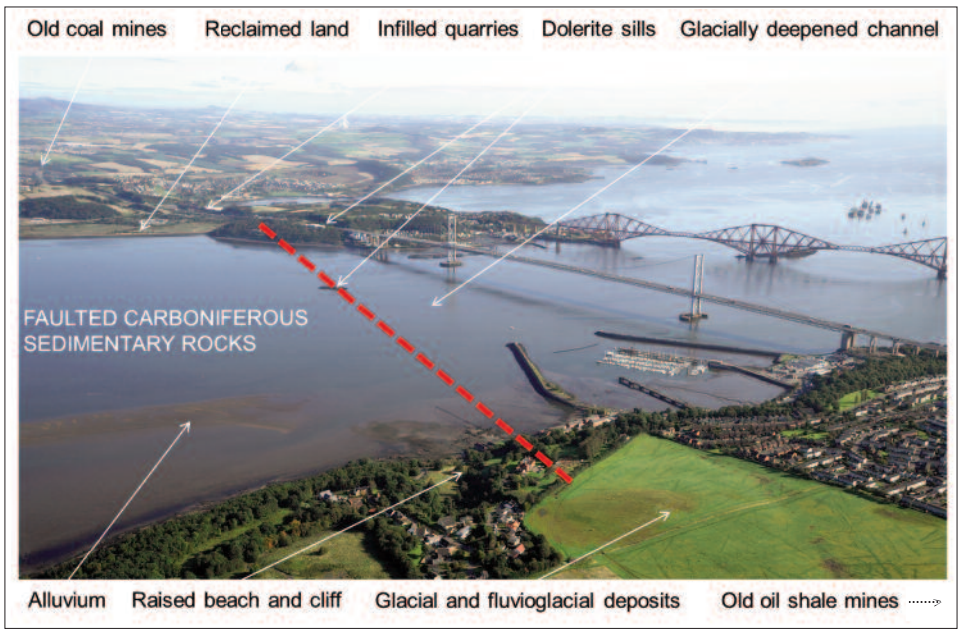


Figure 3 Physical and geological setting of the crossing at Queensferry, looking north-east.

around a tidal islet (Beamer Rock) formed from a thick dolerite sill. Glacial till of Devensian age has been widely deposited on land and on the bed of the Firth, where it is interbedded with fluvio-glacial or glacio-marine sand and gravel deposits. Short lengths of post-glacial sand and gravel raised beach deposits are identifiable on both north and south shores. Present-day deposition in the estuary comprises alluvium with a range of particle sizes from gravel to clay. Hydrological studies suggest that the alluvium is in dynamic equilibrium, moving progressively downstream from fluvial source to the sea, but bed levels and sediment thicknesses remain approximately constant from year to year. The southern shore has a shallow gradient and a large sand bar (the Hopetoun Bank) is exposed at low tides.

Anthropogenic effects include the mining and quarrying already referred to but also the reclamation of land on the north shore by the deposition of sediment dredged from the ports in the Firth, particularly at Rosyth (immediately adjacent) and at Grangemouth (upstream). Dredging to maintain harbour depths continues regularly but the arisings are currently deposited well downstream in the outer Firth.

Strategic approach to the project

The typical phases of an engineering project are:

- investigation
- design
- construction

Investigations are critical to inform the design and construction phases and also the parallel management processes of authorisation (achieving statutory, public and financial approval), procurement (contractually defining roles and responsibilities) and risk management (controlling safety, timescales, cost and quality).

Transport Scotland was responsible for the overall management of the project on behalf of the Scottish Government, with engineering and management support provided by Jacobs Arup Joint Venture. For convenience these organisations together are referred to hereafter as the 'Employer'.

Specific tasks for which the Employer was responsible included:

- obtaining authorisation;
- developing an initial ('Specimen') design and technical specifications;
- procuring a contractor for the detailed design and construction of the works (a 'Design and Build' contract);
- overseeing the contractor's design and construction of the works.

All these activities were undertaken against a background of an overall risk management strategy. Unforeseen ground conditions were identified as a critical risk, with the prospect of delays and cost increases if late changes were required to the design or construction methods. The Employer therefore elected to invest significantly in early ground investigations, minimising uncertainty at all stages of the process by making a comprehensive, high-quality, reliable body of information on ground conditions available to all interested parties.

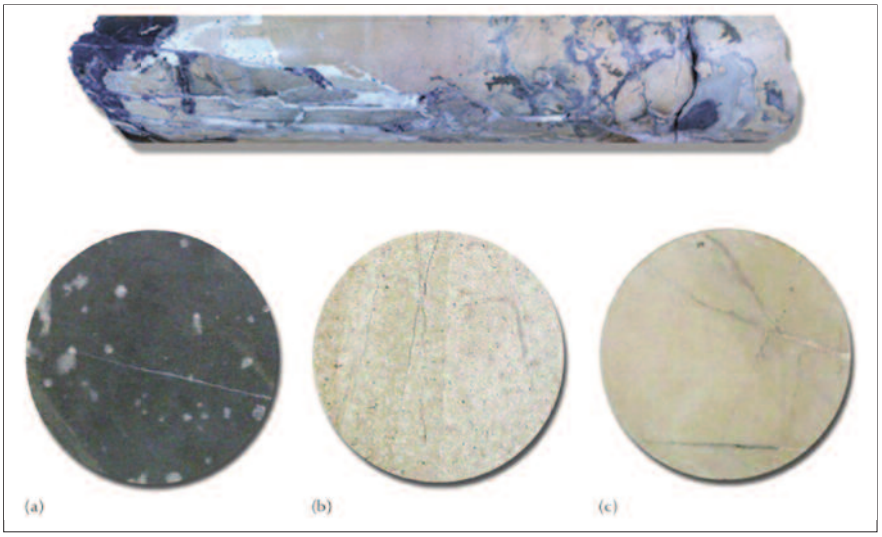


Figure 4 'White Trap': top, core demonstrating complex relationship with surrounding shale; bottom, slices through cores — (a) unaltered fine-grained dolerite; (b) strongly altered medium-grained dolerite with relict igneous texture; (c) completely altered fine-grained dolerite (true 'White Trap').

Notwithstanding the availability of information for design, the Employer required that during construction, the formation (the engineering term for the surface on which the foundation is to be constructed) of each foundation be visually inspected and validated against the design assumptions. The methods adopted to fulfil this requirement are described in later sections.

Additional risk control measures included the Employer's review of the contractor's detailed design and construction proposals and an Employer's requirement for the contractor to carry out full-scale trials of critical geotechnical construction processes (particularly those carried out under water or otherwise difficult to inspect) to demonstrate the effectiveness of the proposed methods.

The following description is arranged in the order Investigation—Design—Construction, and illustrates approaches to the geotechnical issues encountered and the application of the risk management processes outlined above. From an engineering geology point of view, the key questions at each stage are:

- Investigation: Is the information obtained reliable (in quality, coverage and representation of actual ground conditions)?
- Design: Notwithstanding the information available, what design assumptions have to be made?
- Construction: Are the design assumptions valid?

Investigation

The investigation undertaken by the Employer followed the conventional stages of:

- desk study
- site walkover
- intrusive investigation
  (including *in-situ* and laboratory testing)

The process was carried out in accordance with Eurocode 7 and with the UK Design Manual for Roads and Bridges (DMRB).

Reliability of the investigation was assured by independent checking of the process in accordance with the DMRB and by

Figure 5 Engineering geologists in action I: the site walkover — Beamer Rock at low tide.

appointing experienced ground-investigation contractors competent in the relevant international, European and British standards.

The desk study of existing information made extensive use of BGS publications and records, but there was also available a ground investigation from an abortive 1980s scheme for a crossing at this location.

The site walkover included detailed discontinuity mapping of rock outcrops on both shores and on Beamer Rock (Fig. 5), but remote methods were resorted to for the underwater parts of the site. Detailed bathymetry was accompanied by side-scan sonar, magnetometer and seismic surveys. The principal aim of the last survey was to determine rockhead, but the results were inconclusive due to 'gas blanking' — attenuation or scattering of signals by the presence of interstitial gas in the recent seabed alluvium. A separate hydrological study of the estuary was also undertaken.

Intrusive investigation was phased over three years as the project developed. Conventional cable percussion boring in soils (in the engineering sense, here roughly equivalent to 'superficial deposits') and rotary drilling and coring in rock were supplemented by sonic (vibratory) drilling, to penetrate more difficult coarse granular deposits or broken rock, and cone penetrometer for soft seabed sediments and reclaimed land deposits. Samples were taken for laboratory testing and down-borehole tests were carried out on the rock mass *in situ* of which the High-Pressure Dilatometer provided key data for design. Down-hole imaging (acoustic and sonic) and geophysics (gamma ray) supplemented the conventional borehole records.

Figure 6 Ground investigation: jack-up platforms in shallow water at Beamer Rock. Elsewhere on site, the platforms worked in water up to 20m deep.

Normal plant could generally be employed, although overwater boreholes had to be executed from jack-up platforms (Fig. 6). Some ingenuity was required of the contractors in tidal zones, including the fabrication of a bespoke working platform.

About 100 exploratory holes up to 80m deep were sunk for the crossing itself, with a further 1,600 for the connecting roads covering several possible alignment options. For the crossing, *c.* 2km of rock core was retrieved, logged in detail and sub-sampled for laboratory testing (Fig. 7).

Figure 7 Engineering geologists in action II: logging 2km of rock core.

Information from the ground conditions was collated to generate a 'ground model' describing the ground conditions (Fig. 8, *opposite*). The ground conditions found were variable but within the range of conditions generally expected from published knowledge of the area and no particularly difficult engineering geology problems were anticipated. Nevertheless, a robust risk management regime was maintained throughout the following design and construction phases.

All the data gathered from the site works and laboratory testing were recorded both in conventional reports and digitally, using the industry-standard 'AGS format' developed and maintained by the Association of Geotechnical and Geoenvironmental Consultants. This permits direct exchange between users and ready manipulation in a range of generic and proprietary data management, modelling and imaging software.

To further strengthen the tenderers' confidence in the quality, coverage and representativeness of the ground investigation, the third phase of ground investigation was timed to occur during the tender period, with all tenderers invited to contribute their own requirements to the scope of works and to have close scrutiny of the works as they were carried out.

At the end of the tender period, the contract for the detailed design and construction of the scheme was awarded to Forth

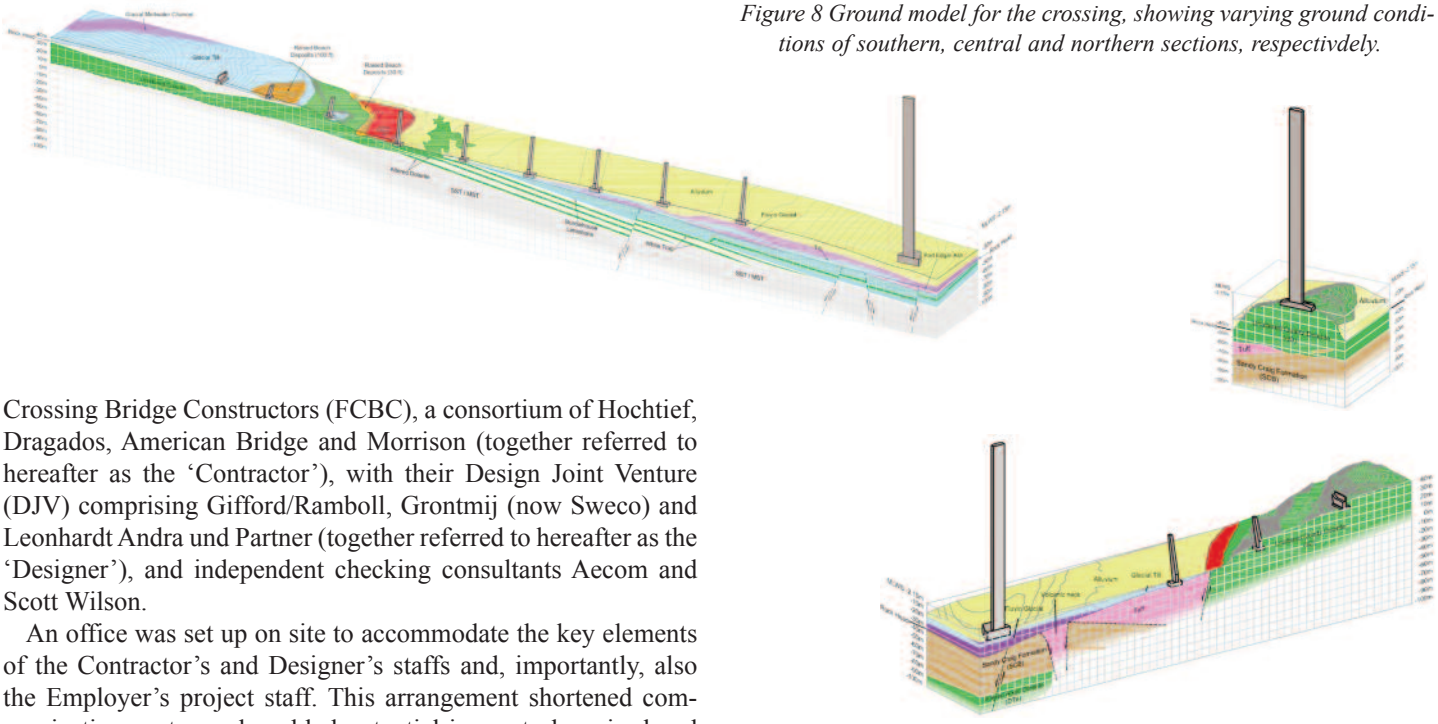


Figure 8 Ground model for the crossing, showing varying ground conditions of southern, central and northern sections, respectivdely.

Crossing Bridge Constructors (FCBC), a consortium of Hochtief, Dragados, American Bridge and Morrison (together referred to hereafter as the 'Contractor'), with their Design Joint Venture (DJV) comprising Gifford/Ramboll, Grontmij (now Sweco) and Leonhardt Andra und Partner (together referred to hereafter as the 'Designer'), and independent checking consultants Aecom and Scott Wilson.

An office was set up on site to accommodate the key elements of the Contractor's and Designer's staffs and, importantly, also the Employer's project staff. This arrangement shortened communication routes and enabled potential issues to be raised and discussed informally before they needed to be addressed through the formal contractual processes.

Design

The Employer had developed a 'Specimen Design' to fix the form and function of the bridge and to demonstrate that viable design solutions existed (a piled foundation solution was provisionally proposed). However, for tendering purposes, only the foundation locations were specified — no constraints were imposed on the form of the foundations, in order to benefit from tenderers' expertise in this field.

On award of the contract, detailed design was undertaken by the Contractor's Designer. The design process has been described by that organisation in other publications (e.g. West *et al.* 2015).

All design outputs, as well as being checked by the Contractor's own independent checker, were reviewed by the Employer for compliance with the contract and the Employer's technical requirements. This process enabled the Employer to fully understand the Designer's and Contractor's intentions, to seek clarification or justification and to influence the proposals and to ensure alignment with the Employer's expectations.

The Designer's foundation design concept was for conventional 'spread' foundations bearing directly onto rock. Pile foundations were considered to introduce otherwise avoidable complexity and risk, and were therefore avoided.

The Designer identified two situations that governed the detailed design of the foundations:

- ship impact — failure by overturning, sliding; and
- temporary balanced cantilever ('Christmas Tree') — failure by overturning, rotation.

Ship-impact loads to be resisted had already been derived by the Employer from probabilistic analysis of ship sizes and velocities available from the port authority.

The 'Christmas Tree' situation arises only temporarily during construction (Fig. 9). Sections of bridge deck are added alternately to each side of the towers to maintain overall balance, but the resulting partial structure remains temporarily vulnerable to asymmetrical forces until linked to the adjacent spans. The Central Tower would support, albeit briefly, the largest such balanced cantilever ever constructed.

These design situations determined the geometry and dimensions of the foundations.

Figure 9 The 'Christmas Tree' situation: the Central Tower became a world record balanced cantilever before the bridge deck was joined to the flanking towers.

Notwithstanding the quantity and quality of ground investigation information available, design assumptions were required to be made about the following parameters for each foundation formation:

- rock type
- rock strength
- fracture spacing and condition

together with the following construction-related characteristics:

- formation gradient
- formation roughness
- formation cleanliness

The Designer required that the design assumptions for all these parameters be validated in situ during construction.

The design situations for each of the 15 foundations of the crossing are summarised in Figure 10.

Construction

Five foundations on land were executed by conventional excavation through the engineering soils (superficial deposits) to expose the rock at the formation level for the foundation. Following inspection, including a discontinuity survey, the Designer's engineering geologist validated the design assumptions and released the formation for construction of the reinforced concrete foundation (Fig. 11).

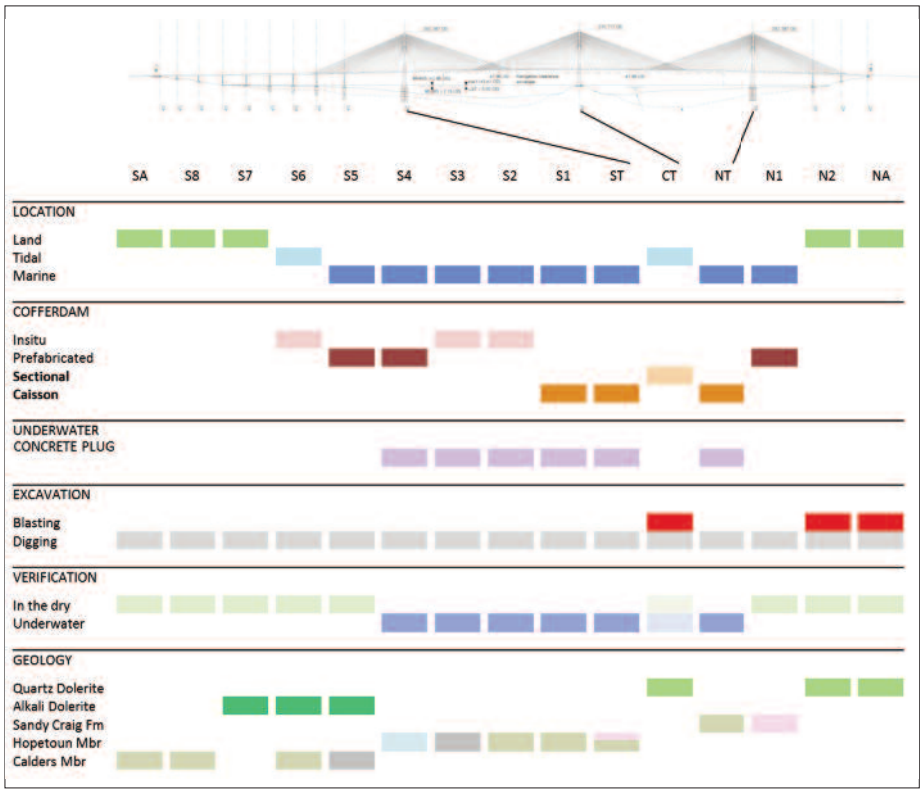
Three shallow-water pier foundations were also conventionally constructed, but within a temporary steel sheet-pile watertight enclosure (cofferdam) sealed to rockhead and dewatered to allow excavation, inspection and foundation construction in the dry.

The lithology at formation level for Pier N1 consisted of tuff, which demonstrated a tendency in the laboratory to disintegrate when placed in water. For unanticipated reasons, this material was exposed to seawater for longer than intended in the N1 cofferdam. When finally dewatered, distinct softening of the surface was observed. A series of short cores were taken and tested, and it was demonstrated that the softening penetrated only a few tens of mm, water penetration being limited by the low permeability of the rock (material and mass). The thin layer of softened material was removed to provide an acceptable formation for the foundation.

Figure 11 Engineering geologists in action III: inspecting formation and validating design assumptions for pier S7 foundation on land.

Three deeper-water pier foundations were also constructed within steel sheet-pile cofferdams, but here the depth of rockhead below sea level meant that full dewatering was not economically viable. An underwater mass concrete plug was poured to partially fill the cofferdam before dewatering and construction of the reinforced concrete foundation. This methodology, however, introduced the issue of validating the rock formation under water before pouring the concrete plug. This issue is explored in more detail in the following descriptions of the tower foundations.

Figure 10 Foundation design situations.



Central Tower foundation: sectional cofferdam

Central Tower was founded on Beamer Rock, the mid-channel tidal islet formed by a quartz-dolerite sill. The foundation formation level necessary for stability required an excavation several metres deep and permanently below sea level. Owing to the competence of the rock mass, blasting was required for the excavation. Only after blasting could a cofferdam be constructed within the excavation to permit foundation construction in the dry, requiring an unconventional cofferdam design composed of rigid prefabricated sections (Fig. 12, *opposite*).

To demonstrate that blasting did not compromise the competence of the rock at the foundation formation level, a full-scale blasting trial was specified. The trial blast was followed by intensive investigation by visual inspection, discontinuity measurement and rock coring, all of which helped specify the necessary blasting

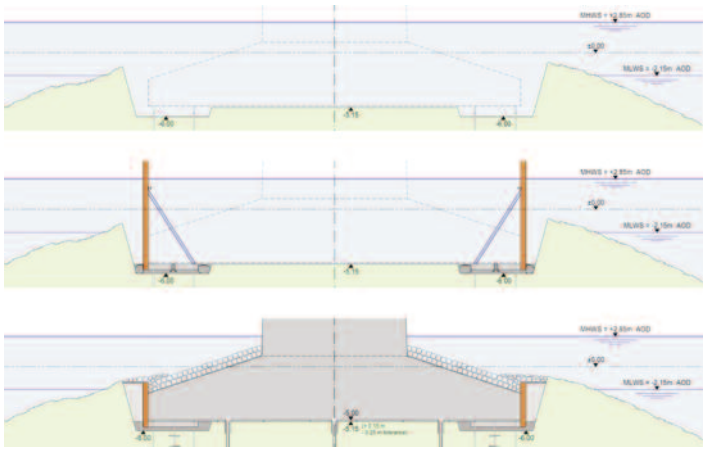


Figure 12 Central Tower foundation construction sequence: top, blast, excavate and shape pocket in Beamer Rock; middle, install cofferdam L-shaped sections and dewater; bottom, construct reinforced concrete structural foundation and cut away cofferdam.

parameters to be developed to minimise blast effects on the underlying rock (Fig. 13).

Production blasting was followed by excavation of the broken rock (for re-use elsewhere on the project) and final shaping of the excavation by a rock-milling head using GPS positioning for precision. The base of the resulting excavation was configured with a broad perimeter trench to accommodate the sectional cofferdam and was permanently below sea level. The shape and levels of the prepared formation were confirmed by bathymetric survey.

The sectional cofferdam was composed of L-shaped units with a steel sheet-pile upright wall attached to a reinforced concrete base, fabricated on land, positioned by floating crane and grouted into place. The bases of the units would carry loads from the reinforced concrete foundation of the tower and therefore the rock on which they sat was included within the formation for the foundation. To comply with the Employer's requirements, the condition of the rock therefore had to be visually inspected and validated against the design assumptions before placement of the cofferdam sections.

This was accomplished by the use of a diver, equipped with video camera, lights and various tools and measuring devices, under the real-time direction of the Designer's engineering geologist who could direct the diver to inspect/measure/test features of interest (Fig. 14). A systematic swim path across the required formation was devised and marked out to ensure that coverage was comprehensive. On completion of the inspection of a work area, the engineering geologist could review the recorded video and compile a plan of the formation, including fracture spacings, lengths and widths. When combined with other data, including confirmatory boreholes, these observations provided sufficient information for the engineering geologist to validate the design assumptions and to release the formation for the construction of the cofferdam. All the information gathered and the conclusion reached were recorded in a Geotechnical Feedback Report.

Once the cofferdam was constructed it was dewatered, exposing the central area of the excavation for inspection by an engineering geologist in dry condition (Fig. 15). As before, validation of the design assumptions enabled construction to proceed.

Figure 13 Engineering geologists in action IV: inspecting the trial blast at Central Tower foundation.

Figure 14 Engineering geologists in action V: directing the diver inspection of the formation of Central Tower foundation.

Figure 15 Central Tower cofferdam dewatered: formation being prepared for inspection, verification and subsequent construction of the reinforced concrete structural foundation.

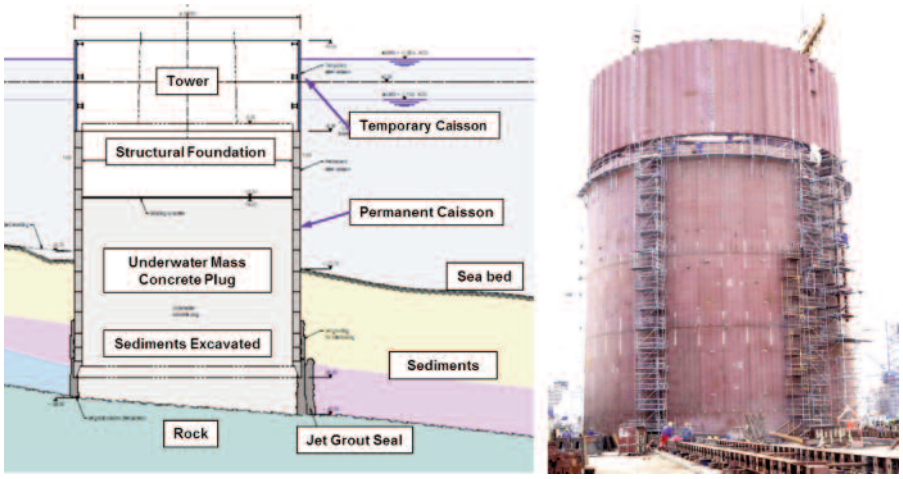


Figure 16 Flanking Tower foundations: left, principles of foundation construction; right, fabrication of permanent and temporary caissons ashore before positioning on seabed.

Flanking tower foundations: caissons

The North and South Towers flanking the Central Tower are located on the shoulders of the channels passing on either side of Beamer Rock, in water depths of up to 20m and with superficial deposits *c*. 20m thick. To construct foundations on rock, the solution adopted was to use caissons: watertight retaining structures sunk progressively through the superficial deposits to reach the proposed founding depths at rockhead. Given the differential head of water of up to 40m between sea level and rockhead, complete dewatering of the caisson would not be practicable. Instead, they would be partially filled with underwater mass concrete to a defined level, dewatered at that point, and then the structural foundation constructed on the top surface of the mass concrete in dry conditions (Fig. 16).

Each caisson comprised a steel cylinder, open top and bottom, of the order of 30m in diameter and 30m in height. The walls were double-skinned to allow for ballasting with water or concrete and were tapered to a cutting edge at the toe. The caissons were positioned on the seabed by GPS and sunk through the superficial deposits using their own weight (with ballast as necessary), lubricated by built-in systems for high-pressure water jetting and bentonite injection, and assisted by progressive excavation of the soils from the interior of the cylinder, eliminating the skin friction on the inside surface. Each caisson was topped by a single-skinned temporary ring *c.* 10m high in order to maintain a safe freeboard during construction.

Rockhead was known to be irregular with level differences of up to several meters at some foundation locations. Once the caisson reached the required depth just above rockhead, the superficial deposits intervening between the caisson toe and rockhead were sealed by jet-grouting, a process of mixing *in-situ* soil and cement grout injected at high-pressure at depth underground. To demonstrate that an effective seal could be achieved, the Contractor was required to carry out a full-scale trial. An area on land having similar superficial deposits (glacial tills and fluvioglacial granular deposits) was identified at the location of a proposed cutting on the southern connecting road. A series of individual jet-grout columns and groups of columns was installed using different injection parameters and then exhumed for inspection and sampling for testing (Fig. 17). The results informed the final process design and demonstrated its effectiveness.

Having sealed the caisson to rockhead, any superficial deposits remaining inside were excavated and the surface of the rock was cleaned using an 'airlift' (suction dredge) device. At this point, to comply with the Employer's requirements, the condition of the rock had to be visually inspected and validated against the design assumptions before placement of any underwater concrete.

Unlike the Central Tower, the depth of water in the caissons precluded the efficient use of divers, their working time at such depths being strictly limited. The proposed alternative was to use a form of remote visual point counting using a bespoke video camera device (the 'camera dome'), supplemented by spot checks by divers. In accordance with the Employer's requirements, a full-scale trial was carried out in a separate specially constructed cofferdam. Following some design improvements, the device emerged as a clear Perspex box *c.* 850mm × 850mm base, 1m high, filled with clean water and fitted with a video camera, powerful lights, a range of orientation and measuring devices, and external jets to clear away any loose silt on the surface to be inspected (Fig. 18).

Inspections were carried out by positioning the camera dome under GPS control following a predetermined systematic grid of points on the cleaned rock surface exposed at the base of the caisson. The entire process was directed by the Designer's engineering geologist, who made observations and measurements in real time and subsequently reviewed the recorded video and compiled a plan of the cleanliness and characteristics of the formation,

Figure 17 Jet grouting trial: columns of soil/cement mixture injected into glacial sediments on land and exhumed for inspection.

Figure 18 The Camera Dome inspection device in its final form.

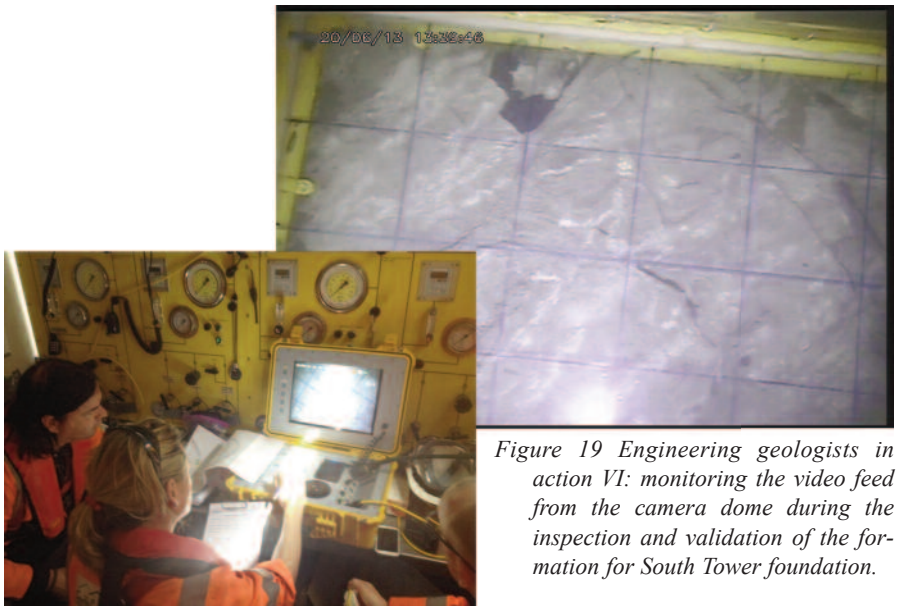


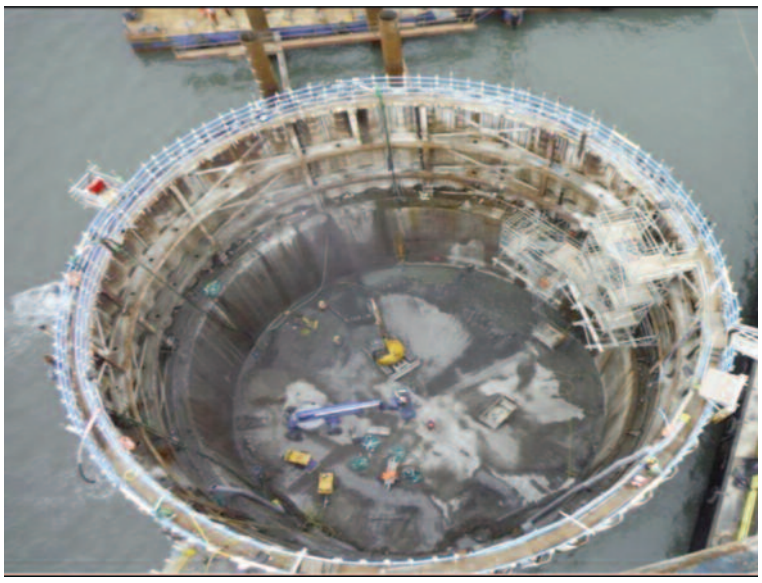
Figure 19 Engineering geologists in action VI: monitoring the video feed from the camera dome during the inspection and validation of the formation for South Tower foundation.

including fracture spacings, lengths and widths, as for the Central Tower (Fig. 19). Divers carried out spot checks of specific locations identified by the engineering geologist. It is notable that the camera dome could operate successfully in conditions of visibility that significantly hampered the divers' activities.

Again as for the Central Tower, the observations combined with other survey data provided information for the engineering geologist to validate the design assumptions and to release the formation for the subsequent construction. All the information gathered and the conclusion reached were recorded in a Geotechnical Feedback Report.

For maximum efficiency, the subsequent underwater concreting of each caisson was carried out as a continuous operation, resulting in what is believed to be a record single non-stop underwater concrete pour of 16,869m^3 in 15 days. After a curing period, the remaining water in the cofferdam was pumped out and construction of the reinforced concrete structural foundation could begin in dry conditions (Fig. 20).

Figure 20 South Tower caisson dewatered: top surface of mass underwater concrete being prepared for construction of the reinforced concrete structural foundation.



Final geotechnical construction activities

As construction of the bridge superstructure approached completion, the final geotechnical construction activity was to place scour protection around certain foundations. Conventional theoretical design techniques were used to determine the need for and characteristics of any scour protection required. In this case, design validation was undertaken by hydrodynamic model testing at the University of Aalborg (Fig. 21). The scour protection comprises a blanket of stone sized to prevent entrainment under the design current speeds and placed on a regulating layer of fill on the seabed around the relevant foundations. Scour protection performance will be further validated by monitoring over the five-year period of Contractor's maintenance liability after completion.

Figure 21 Scour protection design validation by hydrodynamic modelling, University of Aalborg.

Concluding remarks

The foundations for the Queensferry Crossing were successfully and safely completed with the minimum of delay through the combined efforts of engineering geologists and geotechnical engineers employed by the Employer, Designer and Contractor organisations in:

- providing comprehensive reliable information on ground conditions;
- ensuring that design assumptions were validated during construction;
- adopting novel approaches to the inspection of foundation formations; and
- undertaking full-scale construction trials in advance.

Reference

West, S. L., Oligmuller, L., Lee, S., and Meekley, J. 2015 'The Queensferry Crossing – design development of the Caisson foundations' *Proc XVI ECSMGE Geotechnical Engineering for Infrastructure and Development*, 805–10

Book review

Park, Graham, published in 2017, copyright 2018 *Mountains: the Origins of the Earth's Mountain System*s. Edinburgh: Dunedin Academic Press (ISBN 978-1-780-46066-6; 212pp; hardback £29.99)

Mountains are one of the more obvious features of the Earth's surface. They tend to occur in relatively narrow belts and their distribution demands an explanation. This book provides an excellent introduction to the Earth's mountains and their tectonic origins. It is beautifully produced with all illustrations in colour, including clearly drawn diagrams and some stunning photographs.

The first two chapters provide an introduction and a summary of the historical development of ideas on the origins of mountains. Chapter 3 summarises the plate tectonic framework and thus provides simple models of mountain-building. Much of the material in these early chapters will be familiar to OUGS members.

The core of the book comprises a global tour of the world's mountains and their origins. Chapters 4 to 9 move from the western Mediterranean to south-east Asia and focus principally on collisional orogeny associated with the progressive closure of the Tethys Ocean. Chapters 10 to 12 comprise a circum-Pacific tour, where orogenic activity is dominated by volcanism associated with subduction. Each chapter contains a great deal of detail; the plethora of microplates in the western Mediterranean explored in Chapter 4 comes as something of a shock after the 'easy read' of the previous three chapters. Taken together, these core chapters could be heavy going. They are best approached at two levels: a quick read to obtain an overview, followed by the study of individual chapters of interest, when text and diagrams can be reviewed in detail. For each of the chapters there are recommendations for further reading in the recent literature, and references for all source material of the figures are provided.

The penultimate chapter reminds us that the largest mountain range on Earth is almost entirely submarine and it provides a global tour of this mid-ocean ridge system. The final chapter considers older mountain belts; here the author restricts his attention to the Palaeozoic mountain belts associated with the assembly of Pangaea.

This is a very good book for anyone interested in the Earth's mountain systems and their origins. The attractive layout and the colour illustrations make this a great book to browse. Individual chapters may be studied with profit to gain a regional understanding.

—Duncan Woodcock, MA (Cantab), BSc Hons (Open), PhD, Continuing ES student

Book review

Hughes, P. D., and Woodward, J. C. (eds) 2107 *Quaternary Glaciation in the Mediterranean Mountains*. London: Geological Society Special Publication 433 (ISBN 978-1-86239-747-7; hardback, 328pp; £100)

This book is certainly broad in scope and demonstrates how the mountains of the Mediterranean were repeatedly glaciated during the Quaternary ice age. The various papers are by the current experts in the field; the forward and preface show the enthusiasm of the researchers in this field, and their love of the landscapes. For all that this area now rarely has extensive snow and ice cover, there are a wealth of glaciated landscapes available to inspect and study. The book demonstrates that the timings of these glaciations have recently been transformed using uranium-series and cosmogenic isotopes, to provide some of the best datable sequences for mountain glaciation. The southerly latitude, and relatively small size of Mediterranean glaciers, made them particularly responsive to Pleistocene and Holocene climate changes, and an ideal area to study these.

The book starts with the usual, and useful, open access, introductory article on Quaternary glaciation in the Mediterranean mountains: a new synthesis. This also divides the research into pioneer, mapping and advanced stages, as the study commenced, data was collected, then the understanding developed. The other papers then fill in the detail:

'Pleistocene plateau ice fields in the High Atlas, Morocco'
'Quaternary glacial history of the Cantabrian Mountains of northern Spain: a new synthesis'
'Evidence of glacial activity during the Oldest Dryas in the mountains of Spain'
'Did Pyrenean glaciers dance to the beat of global climatic events? Evidence from the Würmian sequence stratigraphy of an ice-dammed palaeolake depocentre in Andorra'
'Glacial history of the Maritime Alps from the Last Glacial Maximum to the Little Ice Age'
'Middle Pleistocene glaciations in the Apennines, Italy: new chronological data and preservation of the glacial record'
'Pleistocene glaciation in Mediterranean Slovenia'
'Middle Pleistocene glaciation, alluvial fan development and sea-level changes in the Bay of Kotor, Montenegro'
'Glacial history of Mt Chelmos, Peloponnesus, Greece'
'The significance of tectonism in the glaciations of Greece'
'Synchronous Last Glacial Maximum across the Anatolian peninsula'
'Cosmogenic ^{36}Cl geochronology of late Quaternary glaciers in the Bolkar Mountains, south central Turkey'
'Late Quaternary glaciations in the eastern Mediterranean'

This book is generally an accessible read, understandably with an emphasis on chronology, with good photographs and diagrams, some of which look the basis for good visits and field trips — studying glacial landscapes in Mediterranean sunshine certainly appeals. An interesting book on a fascinating subject.

— John Lonergan, FGS, BSc OU Geosciences

Scotland's potential contribution to the evolution of dinosaurs in the Middle Jurassic

Neil D. L. Clark

The Hunterian at Kelvin Hall
University of Glasgow
Glasgow G12 8QQ

contact: neil.clark@glasgow.ac.uk

Abstract

Dinosaurs are now well established as part of the Jurassic fauna of Scotland. The dinosaurs that have been found on the Isle of Skye are among the rarest of all dinosaurs due to the world shortage of Middle Jurassic dinosaurs. Although most of these remains are in the form of footprints, there are a few skeletal remains as well. Many of the better-known groups of dinosaurs were only just making an appearance for the first time and Scotland may be able to answer some of the questions regarding their early evolution. We now have a basal eusauropod, early examples of non-neosauropod and possible basal titanosauriform eusauropods, as well as theropod remains that may belong to an early coelurosaur or a possible megalosaurid, basal tyrannosauroid, or dromaeosaurid. The footprints also provide evidence of a rich and diverse dinosaur fauna waiting to be uncovered by further discoveries and research.

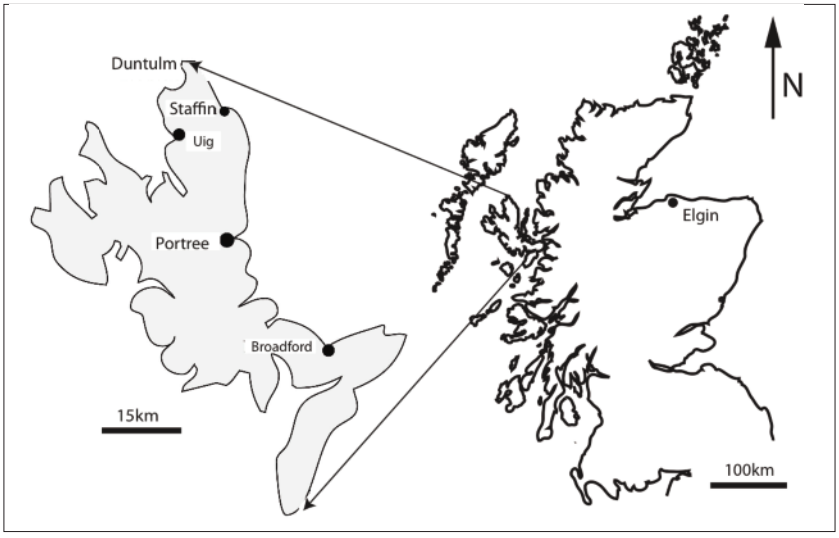
Introduction

Scotland is now well known worldwide for the discoveries of some of the major footsteps in the terrestrialisation of life on Earth. With the earliest known air-breathing invertebrates (Wilson and Anderson 2004), to the earliest tetrapod vertebrates capable of walking on land (Smithson *et al.* 2012), as well as some of the most beautiful preservation of an early Devonian terrestrial ecosystem at Rhynie in Aberdeenshire (Trewin 1996). Perhaps one reason for this was because Scotland has been on the edge of a continent with plenty of tropical shallow seas and river systems from the Ordovician to the Cretaceous. Ephemeral lakes and pools may have accelerated adaptation to terrestrialisation by increasing the pressure (e.g. from gravitation, atmosphere, lack of water, etc) for survival in this new environment (Vecoli *et al.* 2010).

Scotland has also been part of the international news when it was reported that the classification of dinosaurs and their early evolution may have been wrong. It appears that the two groupings of dinosaurs into saurischian and ornithischian may have been over simplistic. A recent study has suggested that theropods and ornithischians may be more closely related to each other than previously thought (Baron *et al.* 2017a). This means that the saurischian dinosaurs now only include the Sauropoda and the Herrerasauridae, and a new group — the Ornithoscelida — include the theropods (including birds) and the ornithischians. The common ancestor to the new group is thought to be exemplified by the Scottish fossil from Lossiemouth, near Elgin: *Saltopus*. This view is controversial and has been the matter of some discussion among vertebrate palaeontologists. The upshot is that a group of researchers have re-analysed the data, and changed some of its interpretation of characters, and come up with a different answer — although they also state that statistically, one phylogenetic tree is not significantly more correct than the other and it is not yet time to be thinking of rewriting the dinosaur textbooks (Langer *et al.* 2017). Over the coming years, there will be a lot more discussion on this issue as researchers add more character differences between the various groups and new species are added to the mix (Baron *et al.* 2017b). Although Scotland may contribute fossils to the analysis, unless the Triassic quarries near Elgin are re-opened, we are unlikely to find new, and more complete, examples of Saltopus to help elucidate the phylogeny of dinosaur groups (Fig. 1).

In this article, I wish to concentrate on the Middle Jurassic dinosaurs from Scotland, as they may hold the key to some of the later diversification of the major groups of the dinosaurs; however, they may be related at a more fundamental level. These dinosaurs have all been found on the Isle of Skye from rocks of Middle Jurassic age, which were part of the Hebridean Basin that extended along the north-west coast of Scotland from Lewis to south of Mull. After the splitting of the northern part of the

Figure 1 Map of Scotland showing the location of the Isle of Skye and Elgin.



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supercontinent Pangaea during the early Jurassic, fingers of shallow marine waters extended northwards into the Hebridean Basin. This seaway occasionally receded, which allowed lagoonal and riverine deposits to accumulate, especially in the Bajocian and Bathonian of the Isle of Skye. It is among these sediments that most of the dinosaurian remains have been uncovered from the Bearreraig Sandstone Formation to the Kilmaluag Formation of Trotternish and Strathaird (Clark and Gavin 2016) (Fig. 2).

Collections

The dinosaurs from the Middle Jurassic of the Isle of Skye are found in the collections of the National Museums of Scotland in Edinburgh, The Hunterian in Glasgow (GLAHM), and the Staffin Museum (SM) on the Isle of Skye.

Sauropod

One of the first bones found from the Jurassic of Skye was a worn limb-bone of a sauropod dinosaur (Clark *et al.* 1995). Since then a few other skeletal remains of sauropods have been found, notably a caudal vertebra (Liston 2004); some teeth (Barret 2006, Clark and Gavin 2016); and some footprints (Brusatte *et al.* 2015, Clark and Gavin 2016). Other possible remains of sauropods have been found and are currently being prepared at the National Museums of Scotland (Fig. 3).

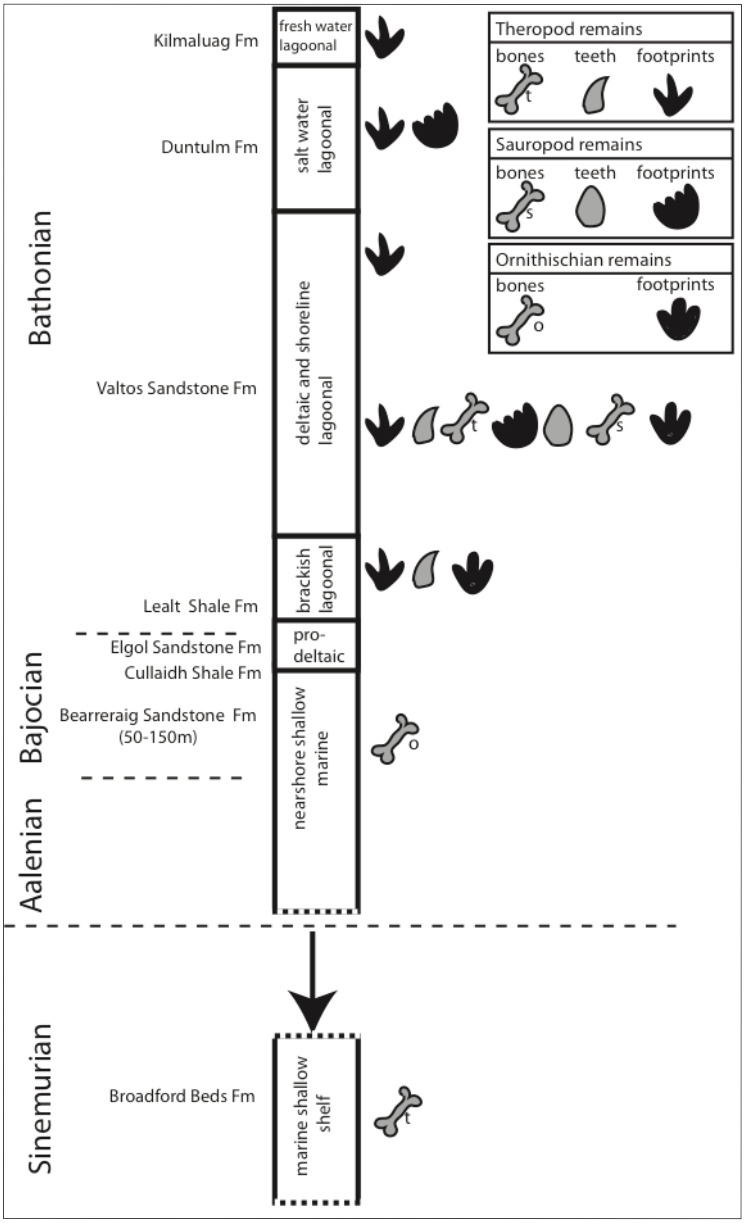


Figure 2 Succession of Jurassic dinosaur-bearing formations on the Isle of Skye and their approximate age, as well as types of dinosaur remains contained within each formation.

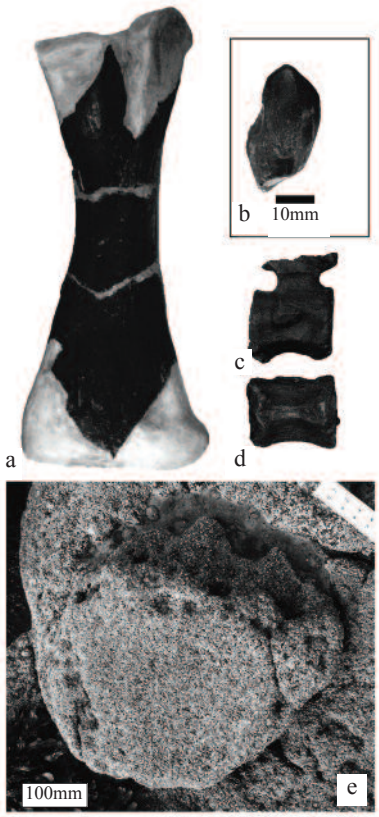


Figure 3 Examples of sauropod remains and footprints from the Trotternish Peninsula, Isle of Skye: (a) cast with interpretative reconstruction of sauropod limb bone from the Valtos Formation near Valtos (SM 1977.1994.1), cast in the Hunterian (GLAHM 109385); (b) sauropod tooth from the Valtos Formation near Ellishadder (SM 1977.2007.1), cast in the Hunterian (GLAHM 131151) (scale = 10mm); (c) lateral view and; (d) ventral view of the caudal vertebra from the Valtos Formation found on the foreshore north of Ellishadder (SM.1977.1996.1), cast in the Hunterian (GLAHM 109384); (e) in situ *sauropod footprint from the Duntulm Formation at Cairidh Ghlumaig near Duntulm Castle. (a), (c), (d), and (e) to same scale (scalebar = 100mm).*

The Sauropodomorpha evolved sometime in the Middle Triassic, giving rise to the Sauropoda by the Late Triassic. By the middle of the Early Jurassic, sauropods such as *Vulcanodon* were alive, and in the Middle Jurassic *Cetiosaurus*, *Shunosaurus* and other Neosauropoda were evolving. Of the footprints, bones and teeth that have been found on Skye, ones from the Valtos Sandstone Formation suggest a more basal sauropod, perhaps of the Gravisauria clade (Clark and Gavin 2016). The large tracksite of the Duntulm Formation at Cairidh Ghlumaig, however, can be assigned to the subgroup Eusauropoda, but probably from a basal eusauropod rather than of the more derived Neosauropoda (Brusatte *et al.* 2015). A tooth from the Kilmaluag Formation at Cladach a'Ghlinne is thought to be a possible basal eusauropod or a basal titanosauriform (a neosauropod), both of which were making their first appearance in the fossil record at this time (Barrett 2006, Evans *et al.* 2006) (Fig. 4, *opposite*).

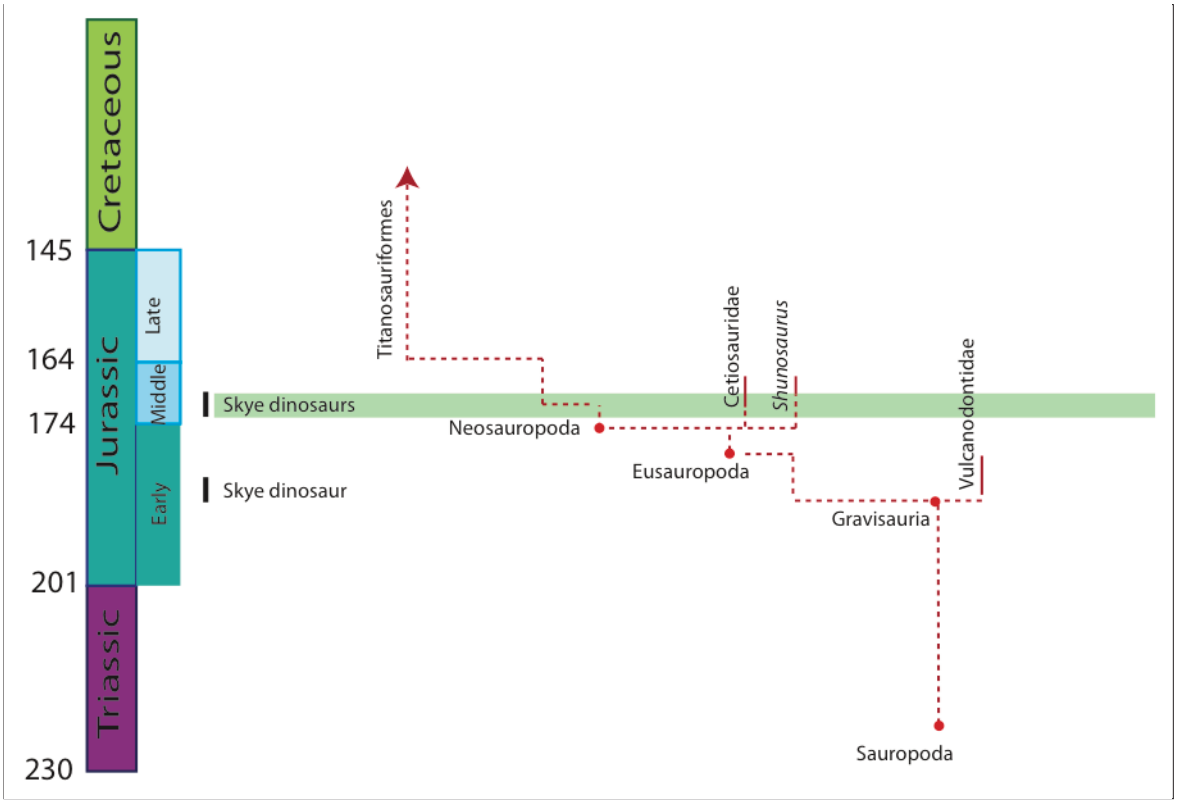


Figure 4 Summarised phylogenetic chart for the Sauropoda as it applies to the Middle Jurassic of the Isle of Skye (adapted from handouts of the detailed phylogenies of dinosaurs by Tom Holtz: https://www.geol.umd.edu/~tholtz/G104FC/104FCHOs.html*).*

Theropod

Middle Jurassic theropod remains are rare on the Isle of Skye, and their existence was initially based entirely on footprint evidence (Clark and Barco Rodriguez 1998, Clark 2001a, Marshall 2005, Clark and Brett-Surman 2008). One theropod tibia was found in the Lower Jurassic Pliensbachian sediments in the Strathaird area in the south of the Isle of Skye (Benton *et al.* 1995).

The oldest record of theropods in the Middle Jurassic of Scotland comes from the mention of a theropod tooth fragment in the Lealt Shale Formation on the Isle of Eigg (Rees and Underwood 2005). Sadly, this tooth has since been lost and cannot be verified. Most of the footprints were found in the sediments of the Valtos Sandstone Formation, and this is also where the first skeletal remains of theropods were found in the form of a tooth and a caudal vertebra (Brusatte and Clark 2015). The caudal vertebra has been tentatively assigned to a basal coelurosaur, possibly a primitive tyrannosauroid (Brusatte and Clark 2015). The tooth is a little more difficult to interpret, but it is thought that it could be dromaeosaur or a basal tyrannosauroid. Other theropod skeletal material has also been recorded from the Kilmaluag Formation; a theropod tooth (collected in 1992), and a potential theropod femur bone (collected in 2003) were both found at Cladach a'Ghlinne (Wills *et al.* 2014) (Fig. 5).

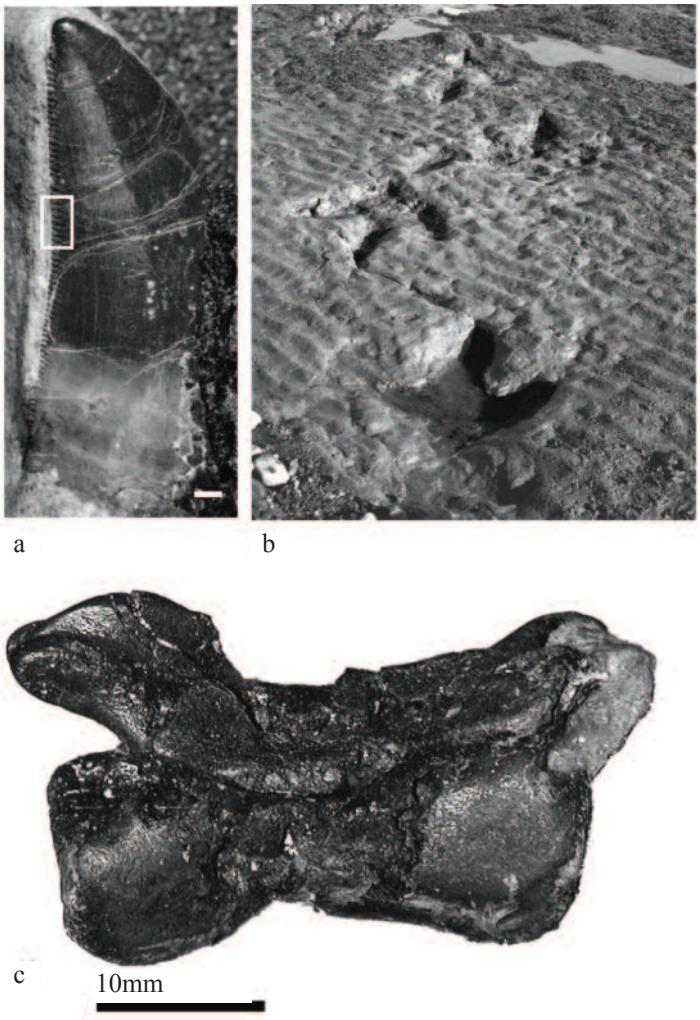
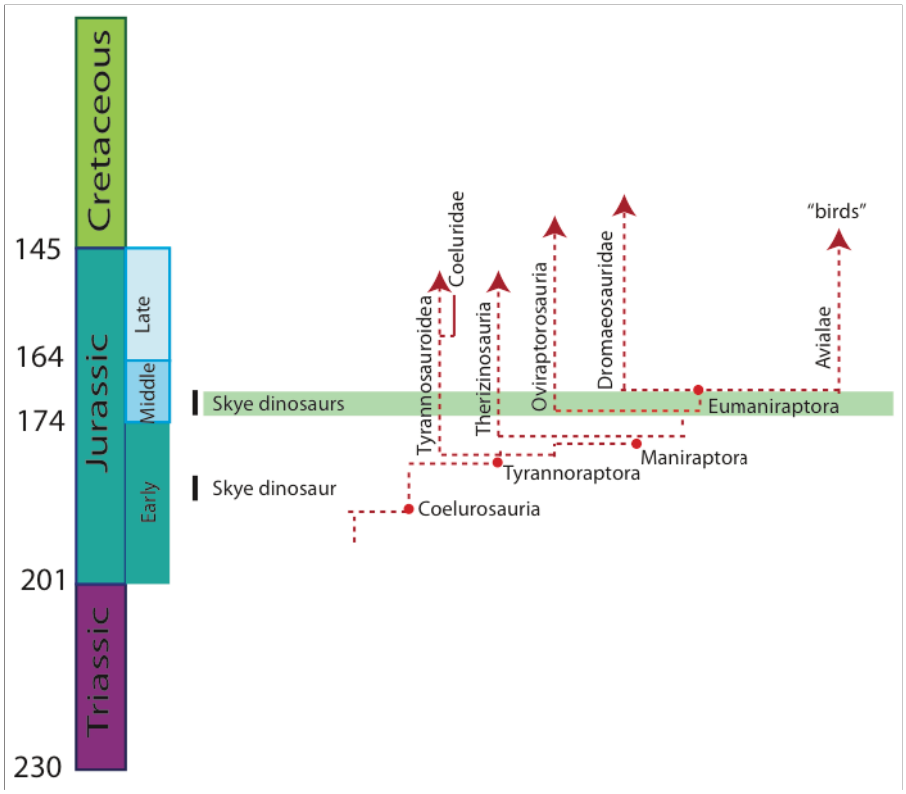


Figure 5 Theropod remains from the Valtos Formation Isle of Skye: (a) tooth (GLAHM 125390a) with inset box emphasising the classic theropod serrated edge (scale = 1mm); (b) large in situ *footprints from the the Duntulm Formation at An Corran near Staffin (GLAHM 114806), cast in the Hunterian (c) caudal vertebra (GLAHM 101240) (scale = 10mm).*

The footprints are less useful in identifying the track-makers and it is not easy to distinguish between tridactyl tracks of theropods from ornithopods (Brusatte and Clark 2015). *Grallator*-like footprints were recorded from the Valtos Sandstone Formation (Clark and Barco Rodriguez 1998, Clark and Brett-Surman 2008) and attempts have been made to identify and distinguish between the *Grallator*, *Eubrontes*, and *Anchisauripus* footprints on the Isle of Skye with little success (Clark *et al.* 2005). A recent hypothesis is that *Eubrontes* represents a basal sauropodomorph, but this is difficult to support on the basis of morphometric data (Clark *et al.* 2005, Getty *et al.* 2017). Most of the footprints are less than 300mm in length and suggest a small- to medium-sized bipedal dinosaur. Footprints from the Duntulm Formation at An Corran are larger than most of the theropod footprints that have been identified and are considered to be theropod on the basis of the sharp claw-like impressions at the tips of the narrow digits (Clark *et al.* 2005). By their size (about 0.5m in maximum length), the track-maker must have been a large dinosaur, perhaps a megalosauroid. The footprints in the Kilmaluag Formation are of a similar size to those of the Valtos Sandstone Formation, although there are quite a number of smaller, probably juvenile tracks present as well (Clark *et al.* 2005) (Fig. 6).

The evolution of the theropods during the Middle Jurassic is an interesting time, with many of the ancestors of the famous Cretaceous dinosaurs originating and diversifying then. The Eumaniraptora that gave rise to the dromaeosaurs and bird lineages as well as the Tyrannoraptora, which includes the tyrannosauroids, therizinosaurs and oviraptorosaurs among many, all evolved at this time.

Figure 6 Summarised phylogenetic chart for the Theropoda as it applies to the Middle Jurassic of the Isle of Skye (adapted from handouts of the detailed phylogenies of dinosaurs by Tom Holtz: https://www.geol.umd.edu/~tholtz/G104FC/104FCHOs.html*).*



Ornithopod

There are a few ornithopod remains on the Isle of Skye from the Middle Jurassic. The first footprint to be found there, although initially thought to have been made by a theropod, was eventually identified as ornithopod (Andrews and Hudson 1984, Delair and Sarjeant 1985).The footprint is thought to have been produced by an iguanodontian like *Camptosaurus*. This was found in the Lealt Shale Formation near Port Earlish. *Camptosaurus* is a Late Jurassic animal of North America and possibly Europe, but there is a closely related dryosaurid from England, from the Callovian, Middle Jurassic rocks of the Oxford Clay Formation that was originally described as a species of *Camptosaurus*.

Other ornithopods that have been found in Skye include a partial ulna and radius of a europodan thyreophoran dinosaur with possible affinities with the stegosaurs (Clark 2001b). Further bones from the same Aalenian to Bajocian rocks of Bearerraig Bay have yet to be prepared and described (Fig. 7, *opppsite*).

Footprints of other possible ornithopods have yet to be described from the Isle of Skye, although the large number of smaller broad tridactyl footprints suggests that some of these are from small ornithopods rather than from theropods. A full study of these is still in progress.

The ornithopods were undergoing a huge evolutionary change in the Middle Jurassic. The earliest Cerapoda are from the Middle Jurassic with the most primitive Marginocephalia first appearing in the Late Jurassic of China (Xu *et al.* 2006) and the Dryosauridae in the Callovian of England (Ruiz-Omeñaca *et al.* 2007). As for the Thyreophora, they first appear in the Late Triassic, but the europodan branch appears to split between the stegosaurs and the ankylosaurs in the Middle Jurassic (Whyte and Romano 2001, Galton 2017). The bones from Scotland appear to be the earliest of the europodan dinosaurs, although it is not possible to state whether it was more closely related to the ankylosaurs or the stegosaurs at this stage. Hopefully further evidence can be drawn from other bones found at the same locality. No other ornithischian bones have been collected from the Middle Jurassic of the Isle of Skye (Fig. 8, *opposite*).

Discussion

The Isle of Skye is providing researchers with a unique insight into the early evolution and diversification of many dinosaur groups that are better known from the Late Jurassic and Cretaceous. With an increase in the number of researchers working on the Middle Jurassic as part of the PalAlba Research Group, the number of new discoveries is increasing substantially. The dinosaurs of the Middle Jurassic of the Isle of Skye have already helped us to better understand the diversification of these groups at this time, but the paucity of good osteological material with specific diagnostic characteristics has prevented the naming of species. The material does allow for group-level identification, however, helping with the broader pattern of diversification of the dinosaurs.

The estuarine and lagoonal sediments of the Middle Jurassic of the Isle of Skye are crucial to our understanding of the global terrestrial biota

of this time. It provides tantalising glimpses into the diversification of theropods (Eumaniraptora and Tyrannoraptora), sauropods (Eusaropoda, Neosauropoda and Titanosauriformes), and ornithopods (Europoda and Cerapoda). In time, it is expected that the Isle of Skye will release many more of its secrets and perhaps even provide us with the earliest information on the evolution of one of the most interesting groups — the birds.

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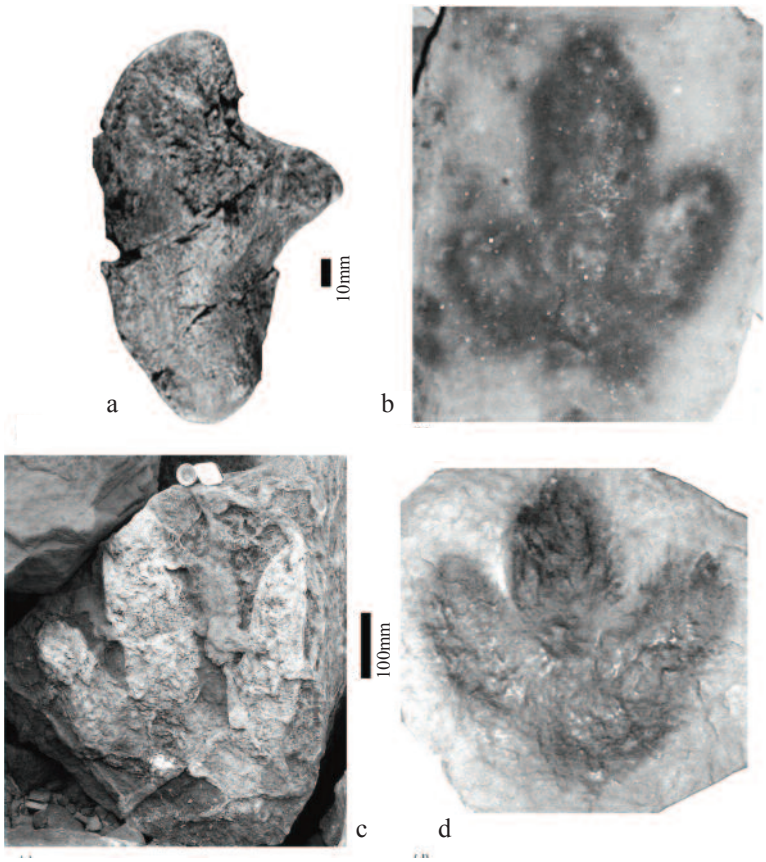

Figure 7 Examples of ornithischian remains, and possible ornithopod footprints from the Trotternish Peninsula, Isle of Skye: (a) ulna of thyreophoran from the Bearreraig Formation (SM 1977.1997.1) (scalebar = 10mm), cast in the Hunterian (GLAHM 114092); (b) Duntulm Formation level B at An Corran, near Staffin; (c) large footprint from the Valtos Formation loose block on foreshore near Dun Dearg, Valtos; (d) Lealt Formation footprint (GLAHM V1980) (scalebar for (b), (c) and (d) = 100mm).

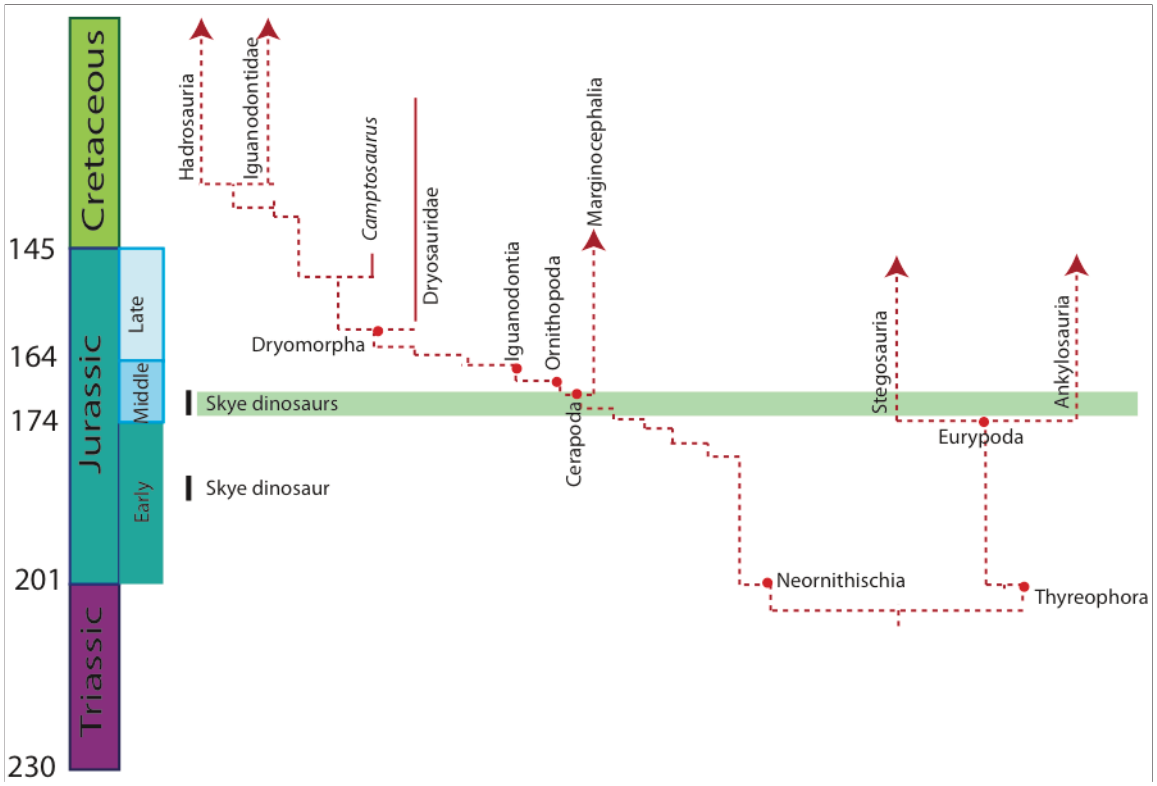

Figure 8 Summarised phylogenetic chart for the Ornithopoda as it applies to the Middle Jurassic of the Isle of Skye (adapted from handouts of the detailed phylogenies of dinosaurs by Tom Holtz: https://www.geol.umd.edu/~tholtz/G104FC/104FCHOs.html).

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Impact of Early Cenozoic uplift and exhumation for unconventional reserves in the Midland Valley Basin*

Prof. John Richard Underhill

Centre for Exploration Geoscience, Applied Geosciences Unit, Institute of Petroleum Engineering
Heriot-Watt University
Edinburgh EH14 4AS UK

contact: J.R.Underhill@hw.ac.uk

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Abstract

Integration of well-calibrated seismic data from the Firth of Forth with field and subsurface data from neighbouring on-shore areas provides important new insights into the structural evolution and petroleum habitat in the Midland Valley of Scotland. The results demonstrate that the NNE–SSW striking Midlothian–Leven Syncline, and its flanking Burntisland and D'Arcy-Cousland anticlines, developed as major growth folds during the Late Palaeozoic under a predominantly dextral strike-slip regime. These syn-sedimentary folds controlled depositional thicknesses, facies and dispersal patterns in early to late Carboniferous (Visean–Westphalian) times. Structural geometries suggest that the folds experienced tightening during Late Carboniferous (Variscan) deformation events before being transected by east–west striking dykes and extensional faulting during the Late Carboniferous (Westphalian D) and Early Permian. Although direct evidence for the basin's post-Permian burial history is no longer present, it can be inferred that the area had at least a kilometre of cover before Palaeogene uplift.

The new understanding of the eastern Midland Valley's structural and subsistence history provides the means to explain the occurrence of petroleum in the basin. Burial of Lower Carboniferous (Mississippian) oil-shale rocks beneath the Midlothian–Leven Syncline now appears to have been the primary driver in the maturation and up-dip migration of waxy crude oil into age-equivalent clastic reservoirs located in the adjacent anticlines, rather than oil generation by direct contact between the source rocks and igneous intrusions. Initial oil charging is thought to have taken place during the Late Carboniferous, was renewed during Mesozoic reburial and appears to continue locally today despite the detrimental effect of significant Early Cenozoic uplift. It is now evident that the basin's limited exploration success has been almost entirely governed by the presence of unbreached palaeostructures lying directly up dip from an oil kitchen, developed in the core of the Midlothian–Leven Syncline during Late Carboniferous and Mesozoic–Recent burial.

Introduction

The aim of this article is to show how the stratigraphical, sedimentological and structural development of Midland Valley Basin governs the petroleum habitat of both conventional and unconventional exploration of shale-oil and gas 'plays' in the Midland Valley of Scotland. I will briefly describe exposures that record the Devonian–Carboniferous depositional record of the Variscan Plate Cycle, and also its Permian–Recent history, as that has led to the subsequent exhumation of the Upper Palaeozoic strata that dominate outcrops in the basin.

Structure of the Midland Valley

The Midland Valley Basin forms a major fault-bounded, Late Palaeozoic sedimentary basin that can be traced from Ayrshire and Renfrewshire in the west, through the central belt to the Angus, Perth, Fife and East Lothian coasts in the east (Fig. 1; Underhill *et al.* 2008). It is *c.* 80km wide, *c.*150km long, and has a WSW–ENE strike orientation. It is bound by the Highland Boundary Fault to the north and by the Southern Uplands fault system to the south. Internally, its structural architecture is dominated by a series of NNE–SSW striking folds that were contemporaneous with Lower Carboniferous deposition and then tightened during the Variscan Orogeny before being transected by E–W striking Permian dykes (Underhill *et al.* 2008). The formation of the folds is consistent with dextral strike-slip motion on the basin-bounding structures. The prominent synclines naturally contain the most complete stratigraphy with Namurian (Millstone Grit) and Westphalian (Coal Measures) present in their axes (e.g. in the Clackmannan and Midlothian-Leven Synclines).

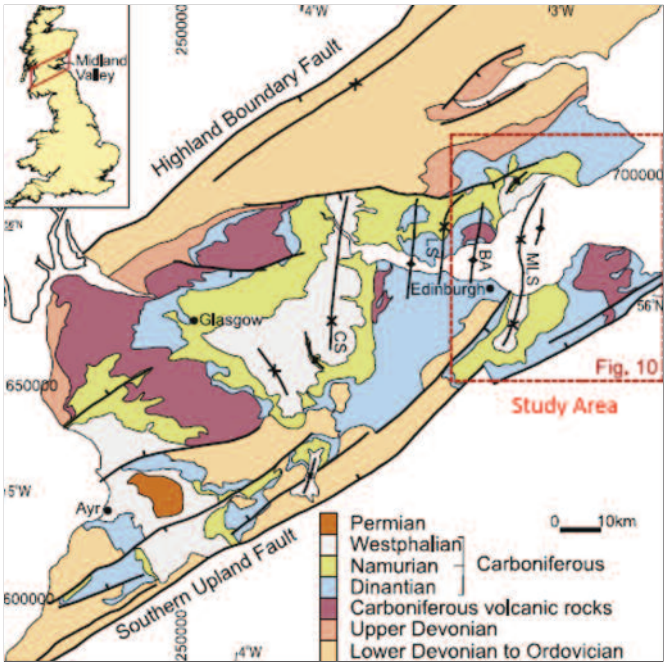

Figure 1 Geology of the Midland Valley Basin, highlighting the main focus area for this study (after Underhill et al. *2008).***

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*** The Editor wishes to apologise for some images in this article being of lower quality than usual — there was insufficient time for the author to obtain higher-resolution figures.*

The basin-bounding faults are long-lived features that were inherited from the Caledonian Orogeny. They still experience some seismic activity in response to intra-plate forces linked to Atlantic Ocean opening. Indeed, the village of Comrie near Perth was even referred to as the 'Shaky Toon', because it was affected by a series of earthquakes in the 19th century, and the first seismological recording station was set up in that area in Scotland.

The Devonian and Carboniferous stratigraphy outcrops throughout the basin, something that enables us to determine the controls on the sedimentary system. The Lower Carboniferous in the eastern parts of the basin (i.e. West Lothian, Midlothian, East Fife and East Lothian) are particularly instructive for understanding the petroleum habitat of the basin, as it contains the main source and reservoir intervals, and hence is the main focus of this article.

The Devonian–Carboniferous succession

The Devonian–Lower Carboniferous succession is superbly displayed in coastal exposures of East Lothian between Siccar Point, Pease Bay and Cove. The base of the succession is marked by major angular unconformity — Hutton's Unconformity (Archer *et al.* 2017). It was first appreciated for its geological significance by Hall, Playfair and Hutton, who arrived at the locality by boat in 1788, when they were seeking to find the boundary between the red rocks and the grey rocks, which they knew made up the coastal exposures at Cockburnspath and St Abbs respectively.

The unconformity is highly rugose, and while it is flat away from the headland, it has significant relief around Siccar Point itself (Fig. 2a). The sedimentary infill comprises brecciated red beds, of Upper Devonian age, onlapping and draping over folded strata of the Lower Palaeozoic. Above that, sandstones and breccias pass up into finer-grained units that are interpreted to represent an abandoned wadi channel. Clast imbrication suggests that they were derived from the denuding Caledonian Mountain range lying to the north.

As one moves west, the succession passes up into a clastic succession consisting of a mixture of aeolian and fluvial red beds, exemplified by the exposures in Pease Bay (Fig. 2b). Trough cross-bedding shows that a N–S, to NE–SW palaeoflow dominated. Towards Cove, the succession becomes even more heterolithic and the first marine bands can be seen near the harbour wall. The succession also includes coals, lagoonal oil-shales and large, red-bed fluvial sandstones (Fig. 2c). By the time one reaches Torness and Barns Ness beyond, the succession has passed into fully marine limestones of Brigantian age.

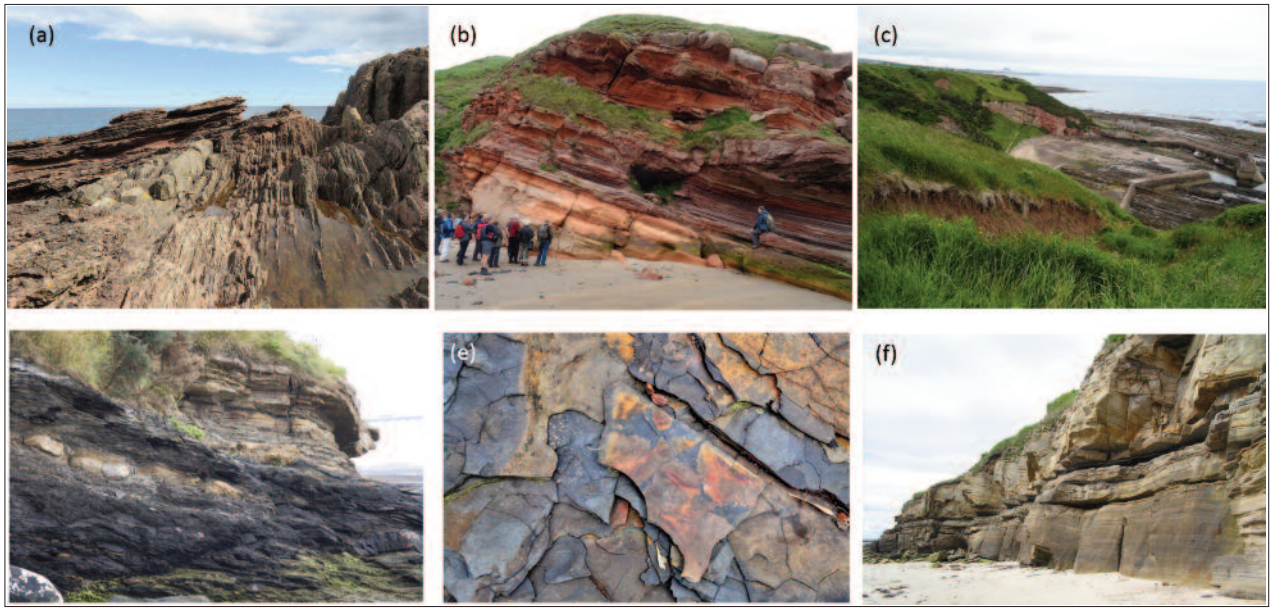
The occurrence of the regionally extensive Lower Limestone Group is an extremely helpful marker, which enables us to determine the complexity of Lower Carboniferous deposition. The litho-stratigraphic terminology, which differs from East Lothian, Fife and West Lothian, brings this evidence to the fore (Fig. 3, *opposite*; Browne *et al.* 1999).

In East Lothian, the Early Carboniferous succession is referred to as the Aberlady Formation and has a quite different disposition from that exposed in West Lothian, which is dominated by oil-shales (Figs 2d and 2e) that were deposited within a lake setting (known as Lake Cadell). The successions are different again in Fife, where the easterly-thickening wedge of axial draining fluvio-deltaic clastic sediments are now ascribed to the Anstruther, Pittenweem, Sandy Craig and Pathhead Formations (Browne *et al.* 1999) (Fig. 2f; the Calciferous Sandstone Measures of old; Greensmith 1962, 1965).

Three tilted depositional domains

From these data it is evident that there were three different depositional domains within the same basin, which basically reflects a basin palaeogeography in which deltas prograded into marine waters that became more prevalent to the south-east but

Figure 2 Field photographs depicting the main elements of the Devonian-Lower Carboniferous deposition in the Midland valley: (a) wadi breccias overlying Hutton's Unconformity at Siccar Point; (b) fluvial and aeolian red beds at Pease Bay; (c) overview of the sedimentary succession at Cove Harbour, highlighting the occurrence of a major inter-distributary fluvial channel within the heterolithic sediments; (d) West Lothian oil-shales exposed on the South Queensferry shoreline: (e) detail of shales belonging to the West Lothian oil-shale that were deposited in a lacustrine environment (Lake Cadell); (f) cliff exposures of Calciferous Sandstone Measures at Ardross Castle in East Fife.



SYSTEM	SUB-SYSTEM	STAGE		SUBSTAGE	HISTORICAL TERMINOLOGY		NEW LITHOSTRATIGRAPHIC CLASSIFICATION			
							GROUPS	FORMATIONS		
								WEST LOTHIAN	EAST LOTHIAN	FIFE
CARBONIFEROUS	PENNSYLVANIAN	Westphalian	C	Bolsovian	UPPER BARREN COAL MEASURES		Coal Measures	Upper Coal Measures		
			B	Duckmantian	MIDDLE COAL MEASURES	PRODUCTIVE COAL MEASURES		Middle Coal Measures		
			A	Langsettian	LOWER COAL MEASURES			Lower Coal Measures		
		Namurian		Yeadonian-Chokierian	PASSAGE GROUP		Clackmannan Group	Passage Formation		
	MISSISSIPPIAN			Arnsbergian	UPPER LIMESTONE GROUP		Bathgate Group	Upper Limestone Formation		
				Pendleian	LIMESTONE COAL GROUP			Limestone Coal Formation		
		Visean		Brigantian	LOWER LIMESTONE GROUP			Lower Limestone Formation		
				Asbian	UPPER OIL-SHALE GROUP	CALCIFEROUS SANDSTONE MEASURES	Strathclyde Group	West Lothian Oil-Shale Formation	Aberlady Formation	Pathhead Formation
										Sandy Craig Fm
				Holkerian to Arundian	LOWER OIL-SHALE GROUP			Gullane Formation (Arthur's Seat Volcanic Formation; Garleton Hills Volcanic Formation)		Pittenweem Fm
										Anstruther Formation
				Chadian	CEMENTSTONE GROUP					Fife Ness Fm
		Tournaisian		Courceyan			Inverclyde Group	Clyde Sandstone Formation		
					UPPER OLD RED SANDSTONE (part)			Ballagan Formation		
								Kinnesswood Formation		

Figure 3 Stratigraphic nomenclature of the Midland Valley. The Lower Carboniferous (Visean) section is marked by a pronounced tripartide geographic subdivision, which reflects important changes in the basin's palaeogeography (after Browne et al. *1999 and Underhill* et al. *2008).*

were stopped from reaching Lake Cadell by a structural barrier that coincides with the Cousland-D'Arcy Anticline (Fig. 4; Loftus and Greensmith 1998).

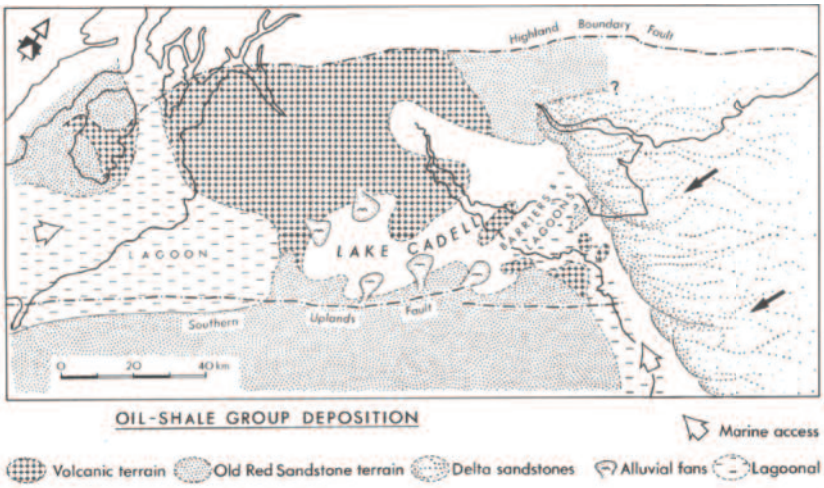
A W–E striking structural transect to the south of Edinburgh shows the disposition of the Midlothian Syncline relative to the steep reverse Pentland Fault to the west and to the Cousland-D'Arcy Anticline on its eastern flank (Fig. 5, *overleaf*). The latter is characterised by smaller (parasitic) closures, which produced hydrocarbons on test. In fact, the gas lights of Musselburgh were supplied with gas from these closures for a couple of decades.

Almost 30 years ago the Conoco-Phillips oil company took an offshore license in the Firth of Forth with a view to testing whether the trend containing onshore fields might continue offshore and decided that there are oil and gas fields. They acquired a grid of 2D seismic data and on the basis of their interpretation and resultant maps, drilled a borehole called Firth of Forth-1 or 25/26-1 (Fig. 6, *overleaf*), which discovered an uncommercial quantity of gas. The subsurface data (seismic and well) provided important calibration of the offshore that not only showed the deltaic wedge, but also showed that it inter-digitated with distal sediments over the anticline itself (Fig. 6; Underhill *et al.* 2008).

So much for what we can see or infer from the subsurface using the rock column, what about what we can infer about the post-depositional history? In order to do so, it is important to view the Midland Valley through a different regional lens and call upon data from a wider perspective, beginning with a geological map of the British Isles. From that it is self-evident that while the oldest rocks outcrop in Lewis and Harris, the youngest rocks occur in south-east England. Indeed, as we pass from north-west to south-east in general we just see a younger and younger stratigraphy outcropping, something that testifies to a down-to-the-east tilt resulting from differential uplift of the UK, with the greatest amount of uplift occurring to the north-west.

As that tilt affects the whole of the British Isles, all the sedimentary basins of the UK are impacted. Furthermore, it is clear from the disposition of strata in many basins that anticlines now characterise areas that were once major basins and have been structurally inverted (e.g. the Wessex, Weald and Cleveland Basins). It is the combination of the Variscan deformation, tilt of the UK and structural inversion have led to the surface outcropping of Devonian–Carboniferous sediments in the Midland Valley.

Figure 4 Palaeogeographic reconstruction of Lower Carboniferous (Visean) deposition showing the extent of deltaic deposition, the position of Lake Cadell and the south-easterly marine influence (after Loftus and Greensmith 1988).



Work that we have undertaken at Heriot-Watt University has been to look at seismic records in and around Scotland, including those that extend beyond the Midland Valley into the North Sea (Fig. 7, *page 59*). These data highlight the regional nature of the west-to-east dip caused by the tilt. Interpretation of recently acquired seismic data demonstrates the regional tilt (Fig. 8, *page 59*). When calibrated by biostratigraphy derived from borehole sampling, it is possible to map the seismic horizons, and trace them until they come to subcrop. By dating the oldest sediments above and the youngest sediments below we can show that this event occurred *c.* 55Ma (Underhill 2001).

Reference to British Geological Survey's mapping that combines the onshore and offshore geology shows

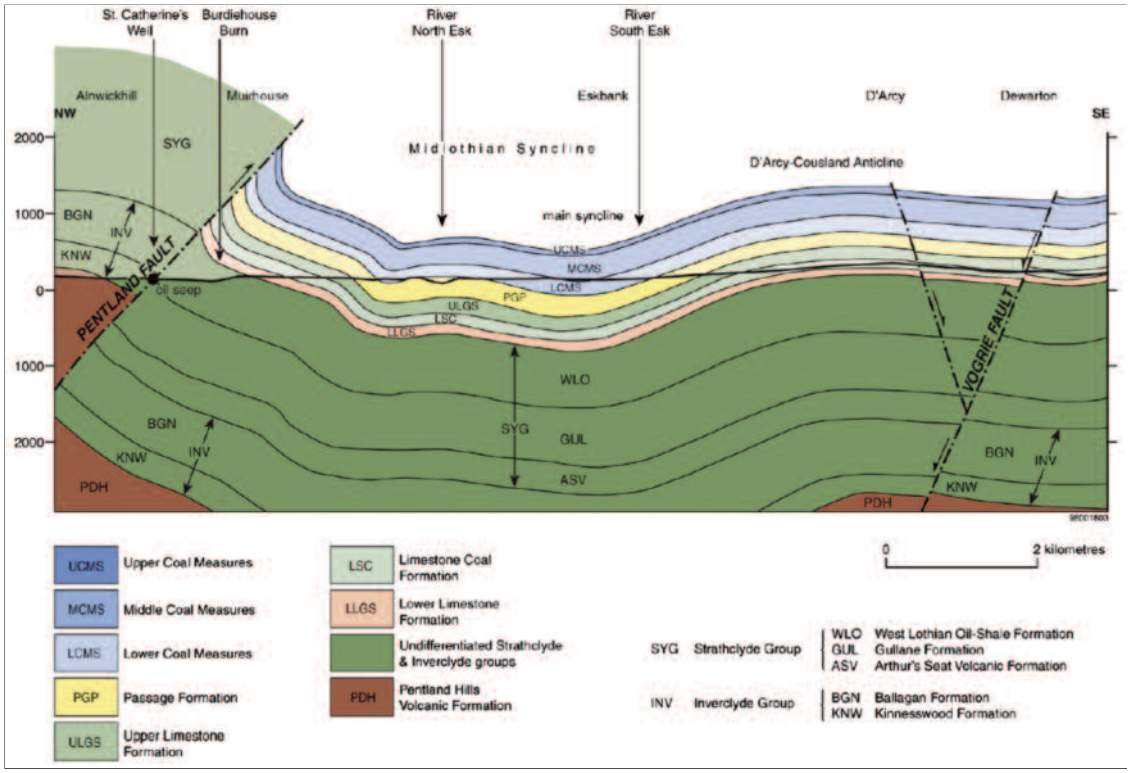


Figure 5 W–E cross-section of the Midlothian Syncline (Underhill et al. *2008). The western margin is marked by the Pentland Fault, an important reverse fault along which oil seeps occur. Its eastern flank consists of an anticline that housed oil and gas fields (Hallett* et al. *1988).*

that the key surface that charts the 55Ma uplift and resultant tilt runs all the way down, parallel to but offshore from the east coasts of Scotland and England. This uplift is coincident with the time just after the volcanic intrusions west of Britain that form part of the Tertiary Igneous Province.

What we have also been able to do is to collect samples across the exhumed part of Scotland and demonstrate that there is a null point (or correlative conformity), to the west of which uplift occurred and to the east of which subsidence continued unabated. As one moves to the west the data suggest that there is 1km, then 2km, and eventually up to 3km of uplift that took place at this time across Scotland, and that led to the exhumation of Precambrian rocks in the Outer Hebrides. Similar magnitudes have also recently been observed in the eastern counties of England (Green *et al.* 2018); and the resultant erosion is also shown by the variable subcrop of the Chalk (Gale and Lovell 2017). It is amazing to think that we are only now waking up to the full ramifications of the geological map that records these processes and events. The fact that the whole of Britain has been uplifted is something that has been staring us in the face for 200 years.

What was the driver for the uplift that culminated *c.* 55Ma ago? The British Isles were at an active plate margin at that time. And immediately before that, what we now know as the Iceland Hot-Spot was created *c.* 60–55Ma, just before the Atlantic opening, causing prolonged and intensive igneous activity west of Britain. Arran, Mull, Skye, Rhum and other islands were created, as well as the Giant's Causeway in Northern Ireland. These igneous intrusions and volcanic extrusions took place immediately before the Atlantic opening *c.* 60–55Ma. The opening produced the first oceanic crust between the UK and Greenland *c.* 54–55Ma. The impact of these processes — the development of the proto-Iceland Hot-Spot, the opening of the Atlantic and the deformation induced by the processes — are the cause and effect of Palaeogene uplift and subsequent basin inversion that can be observed across the UK; and they also affect the Midland Valley of Scotland and other areas.

Conclusions for the petrolem industry

What does all this information mean for the petroleum system of onshore sedimentary basins in general and for the Midland Valley in particular? It had an oil-shale industry and a conventional exploration history. Some of the data also suggest that there are large unconventional resources (Monaghan 2014).

Starting in the west, there was a major shale-oil industry centred on West Lothian until the 1960s and the mining activity therein was effectively limited by the extent Lake Cadell. Its occurrence shows that the basin has a source rock with high total organic carbon (TOC) content. As in other petroleum provinces, if it was or is buried deep enough the potential exists for it to be heated up sufficiently for oil or gas to be expelled and come to

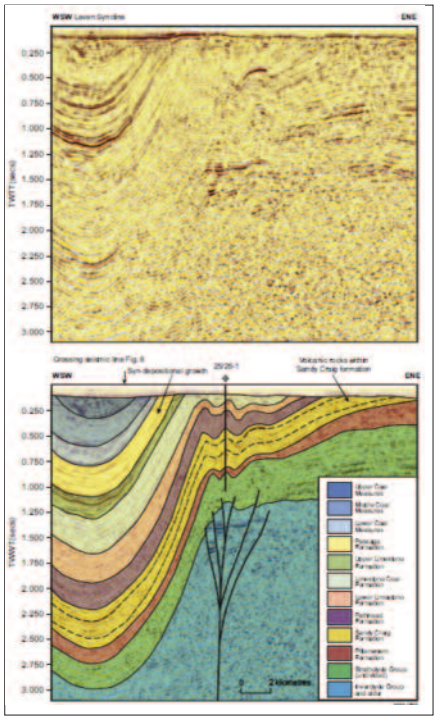


Figure 6 A W–E striking seismic section from offshore waters of the Firth of Forth, showing the nature of the Midlothian-Leven Syncline and the position of Conoco's 25/26-1 borehole. Stratigraphic and temperature data from the well makes it possible to map key horizons, including the West Lothian Oil Shales, thus enabling the determination of the extent of the oil kitchen area.

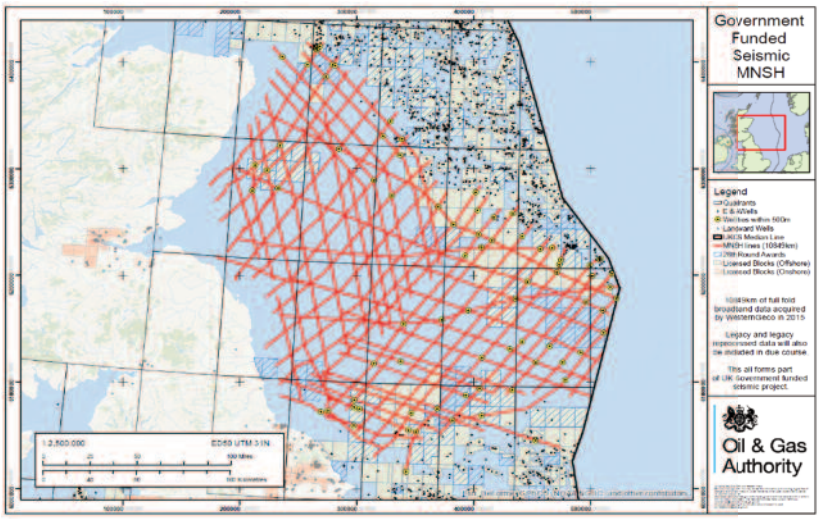


Figure 7 Grid of seismic data recently acquired by the Oil and Gas Authority (OGA), which enables subsurface mapping east of the Midland Valley.

smaller than the large resource estimates upon which exploration is predicated.

So much for explaining the conventional oil and gas deposits, but what does this mean for an unconventional exploration future? As a starting point it is probably worth highlighting the differences between those basins that give shale-gas in the USA and those in the UK, such as the Midland Valley. The successful 'plays' in the USA are deeply buried — at their maximum depth and pressurised — such that the source rock is currently mature. The best sites show stratigraphic continuity, lacking of folding and faulting, meaning that you can drill horizontally into the same mature, productive interval for long distances. In contrast, the uplift of sedimentary basins in the UK makes them cooler, depressurised and deformed, such that it is more difficult to find any mature source intervals or to drill for great

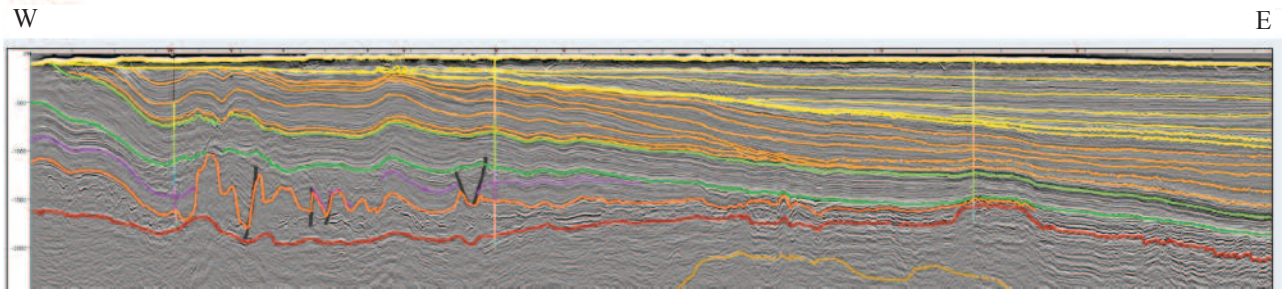


*Figure 8 W–E striking seismic line from the OGA survey, illustrating the down-to-the-east tilt that affects the UK. Dating of the horizons demonstrates that the tilt reached its culmination during the Paleogene (*c. *55Ma).*

the surface today. One major clue that an active conventional petroleum system exists in the basin comes from the natural oil seep along the Pentland Fault at St Catherine's Well (Fig. 9) in Liberton, a suburb of Edinburgh. Its occurrence led to the foundation of a hospital for skin diseases at the site. People unfortunately afflicted by these ailments had a shale-oil spread on their bodies to make their life more manageable. The well has historical significance too, for many Scottish monarchs came here, including James IV in 1504 and later James VI (James I of Great Britain). The latter had the site protected in 1617, but it was destroyed by Cromwell's troops in 1650. The present structure is the restoration of 1889, opposite Mortonhall Crematorium, in the grounds of the Balm Well pub.

St Catherine's Well tells us, therefore, that at sometime in the past an oil-source rock was buried deep enough to be heated to maturity in a 'kitchen area'. That means the source rock is in a sort of 'Goldilocks Zone': not too hot, not too cold, just about right, for oil to come out, either in the past or the present day. The fact that oil and gas fields occur within the anticlines of Cousland and D'Arcy shows us that oil migrated from a kitchen area to reside in the traps (Hallett *et al*. 1988).

By reconstructing the subsidence and burial history of the Lower Carboniferous source rocks in different parts of the basin it is possible to show that this kitchen resides in a small oval-shaped area beneath the Midlothian-Leven Syncline buried beneath the offshore waters of the Firth of Forth, and that petroleum migrated up-dip to fill neighbouring closures (Fig. 10, o*verleaf*; Underhill *et al.* 2008). The kitchen area is the effective limit of shale-oil maturity today, meaning that the unconventional reserves in the basin are likely to be considerably

distances in them. The problem with uplift has been recognised in other basins as well, where similar amounts of uplift have led to unsuccessful exploration for shale-gas (e.g. in the Galilee Basin of Australia; L'Anson *et al.* 2018).

That is not to say that companies who are going out to explore for shale-gas will not be successful. They might be, but only at a local (licence block) scale rather than on the industrial scale that the UK needs to satisfy its gas needs (Underhill 2017).

Figure 9 St Catherine's Well oil seep in the grounds of the Balm Well public house opposite Mortonhall Crematorium near Liberton. The significance of the site is that it demonstrates that there was or is an active kitchen area in which the West Lothian oil-shale is mature and from which oil was expelled or is still migrating.

Concluding remarks

So, what I hope I have been able to do is to outline how important it is to understand the full geological evolution when seeking to assess the petroleum habitat of a basin like the Midland Valley. Gaining insight about the basin's subsidence history must go beyond just what is exposed at the surface and must also factor in subsurface data and regional knowledge from beyond the immediate area. In the case of the Midland Valley, it is the understanding of the subsequent uplift and deformation that impacted the basin that has profound implications for both conventional and unconventional Lower Carboniferous petroleum systems. The results lead to the conclusion that events 55 million years ago have been detrimental for large-scale shale-gas extraction.

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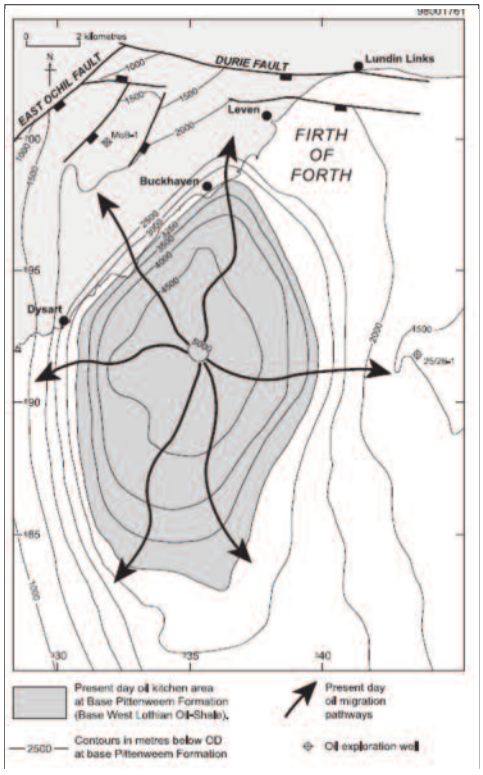


Figure 10 Integration of the mapping with temperature gradient from the Conoco well enables us to determine the extent of the active kitchen area (Underhill et al. *2008). While this information explains the occurrence of oil and gas fields hosted by Lower Carboniferous reservoirs on its eastern flanks, its relatively limited area implies that unconventional resources are much more limited than published estimates have suggested.*

Scotland's Palaeocene lava fields: volcanism, sedimentation and ecosystems during the development of the Hebridean Igneous Province

Dr Ian T. Williamson

Introduction

Okay, let's face it, basalt is a strong contender for the 'most boring rock in the entire universe award'. Surely, there is nothing quite so pointless and tedious than the study of a large area of old, cold, grey-black basaltic rocks hundreds of metres thick, and the exploration of landscapes composed of little else? This contribution presents a very different, personal view of one suite of ancient, predominantly basalt lavas, those that were erupted during the Palaeocene in what is now the Inner Hebrides of north-west Scotland. Seen as less spectacular and charismatic than the associated mountain ranges of Skye, Rum and central Mull, these ancient lava fields are not the monotonous piles of boring basalt and endless tracts of wet, boggy grassland beset by mist and midges as commonly portrayed. In fact, they are surprisingly rich in detail and geodiversity, as their formation, and the evolution of the Palaeocene landscape involved a combination of coeval volcanic, tectonic, sedimentary and biotic processes.

Having placed Hebridean Palaeocene volcanism within the wider context, this short review first summarises the location, stratigraphy and age relationships of the lava fields, and outlines key aspects of geochemistry and petrogenesis. It then looks at the physical, field-based evidence for the nature and styles of volcanic, sedimentary and biotic systems operating at the time, and how we can use these to inform palaeogeographical reconstructions. In concluding, it considers present-day landscape character and the way these lava field landscapes have influenced and inspired people.

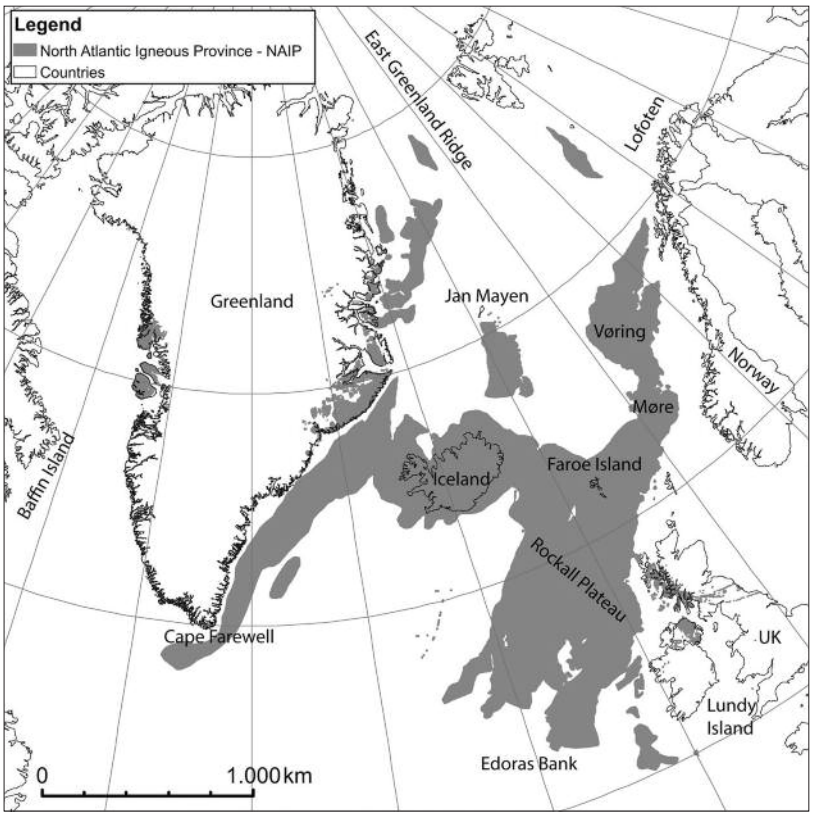
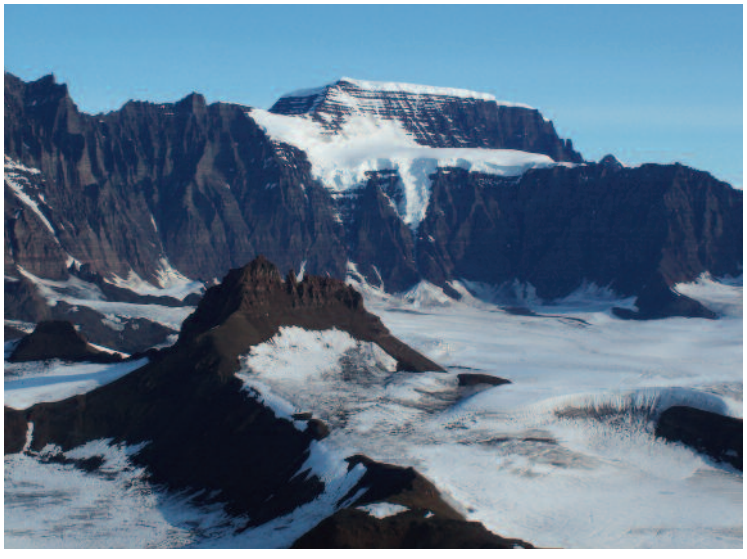


Figure 1 Map showing the location and extent of the North Atlantic Igneous Super Province.

The North Atlantic Igneous Superprovince

During the Palaeocene, the period between roughly 61–58Ma saw the emplacement of volcanic fields, central volcanoes and intrusive complexes along the continental margins of Greenland and north-western Europe. This volcanism was attendant upon the early stages of sea-floor spreading forming the North East Atlantic Ocean, and it created what is termed the North Atlantic Igneous Superprovince (NAISP). Petrogenetic models feature upwelling and decompressive melting of anomalously hot mantle material, most invoking the generation of a 'plume' that impacted the lower lithosphere beneath Greenland. Challenging this, other models prefer a combination of plate tectonics, lithospheric thinning, and the production of variable decompressive upper mantle melts along major rift zones (Figs 1 and 2).

Figure 2 North Atlantic Igneous Super Province: continental flood-basalt lava sequence, east Greenland.



Today, the UK on-shore vestiges of this volcanism crop out extensively in the Inner Hebrides and in Northern Ireland, where they form dramatic mountain landscapes, rugged cliff-margined islands, and bleak stepped plateaux. The lava fields described in this article are an integral and significant component of the Scottish sector, now referred to as the Hebridean Igneous Province (HIP).

The Hebridean Igneous Province

The principal components of the HIP are flood-basalt, intrusive igneous complexes, sill complexes, and a myriad of 'minor' intrusions, including regional dyke swarms, suites of cone-sheets and scattered plugs. Sedimentary units, also present, form less than 1% of the stratigraphy, but are significant components when considering the landscape dynamics of the time.

Apart from peripherally, where the lavas sit on metamorphic 'basement', a considerable thickness of Mesozoic strata underlies

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them in two half-graben basins — the Sea of the Hebrides Basin and the Inner Hebrides Basin. These strata comprise up to 500m of syn-rift Triassic conglomerates, breccias and sandstones, overlain by *c*. 1km of Jurassic to Cretaceous marine and estuarine clastic and chemical sediments that were deposited under eustatically and tectonically controlled conditions.

The lava fields of the HIP

The HIP includes two principal lava fields, those of Skye-Canna-Raasay and Mull-Morvern-Ardnamurchan. A third area of lavas, a sequence exposed on Eigg and Muck may be an outlying extension of the Mull-Morvern-Ardnamurchan field. Including submarine extensions, the combined fields crop out over an area over 4,000km^2, but in the past, would have extended well beyond their present-day limits (Figs 3–6).

Age relationships

Relationships between the lava fields, and with associated central complexes, have been established through field evidence and radiometric dating, with the indication that the lava fields were emplaced within a *c.* 3 million-year period — rapidly, in geological terms.

On Rum, remnants of the early Skye sequence (Canna Lava Formation; *c.* 60Ma) are unconformable upon, and include conglomerates derived from, an unroofed and vigorously eroding Rum Central Complex (*c.* 61Ma). Equivalent formations, also

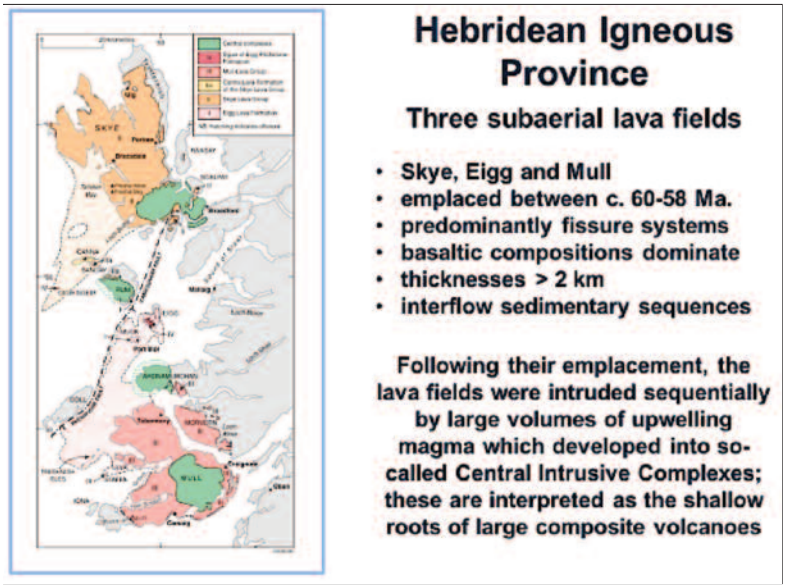

Hebridean Igneous Province
Three subaerial lava fields
• Skye, Eigg and Mull
• emplaced between c. 60-58 Ma.
• predominantly fissure systems
• basaltic compositions dominate
• thicknesses > 2 km
• interflow sedimentary sequences
Following their emplacement, the lava fields were intruded sequentially by large volumes of upwelling magma which developed into so-called Central Intrusive Complexes; these are interpreted as the shallow roots of large composite volcanoes

Figure 3 Map showing the location and extent of the Hebridean Igneous Province lava fields.

with conglomerates bearing Rum-derived clasts, are seen in west-central Skye. This phase of volcanism continued, on Skye, until *c.* 58.9Ma, at which time late-stage, olivine tholeiite flows were erupted, coincident with development of the early (Cuillin) Central Complex. As the pre-tholeiite lava field is thermally metamorphosed in proximity to the Complex it clearly pre-dates it, providing clear field evidence for the relative ages of the Rum and Skye central volcanoes (Fig. 7, *opposite*).

Isotopic age determinations suggest that the Skye and Mull lava fields are more-or-less contemporaries. Volcanic activity on Mull may have begun as early as 60.5Ma, with the lavas initially infilling of a major structural graben before spilling out and overstepping the surrounding topography. Like Skye, metamorphism of the lava field indicates that it predates the associated Central Complex (*c.* 58.5Ma).

There is no unequivocally pre-Complex lava field on Rum, although there are some heavily fractured and thermally altered basalts within the Complex's Main Ring Fault. Their affinity is not known with any certainty, but they are thought by some to have been part of the Eigg-Muck lava field. It is unclear whether the Eigg-Muck lavas are part of a former Rum lava field, an extension of the Mull lava field or an independent field. However, a tuff stratigraphically low in the sequence is dated

*Figure 4 (left top) Skye Lava Field: present on Skye, Raasay, Scalpay, Canna-Sanday and north-west Rum, it comprises three significant units — bottom to top, the Portree Hyaloclastite Formation (*c. *30m), laterally equivalent and overlapping Lava Formations (*c. *1,500m +) and the Talisker Lava Formation (*c. *120m). Shown here is the Beinn Edra Formation, the Storr cliffs and the Old Man of Storr, north-east Skye.*

*Figure 5 (left middle) Eigg Lava Field: present on Eigg, Muck and possibly south-east Rum. Shown here are flat-lying basaltic lavas (*c. *400m in total) overlain unconformably by the An Sgurr, lava-like rheomorphic ignimbrite (*c. *120m). The latter also forms the small island and skerries of Oigh-Sgeir south-west of Canna.*

*Figure 6 (left bottom) Mull Lava Field: present on Mull and adjacent islands (Staffa, Ulva, Gometra, Little Colonsay, Eorsa, Treshnish Isles), Morvern and Ardnamurchan. Shown here is an example from the Staffa Lava Formation. This formation of columnar-jointed flows, hyaloclastite breccias and sedimentary units, is up to 300m thick, and overlain by 1,200m of the Mull Plateau Lava Formation (*see also *Fig. 10).*

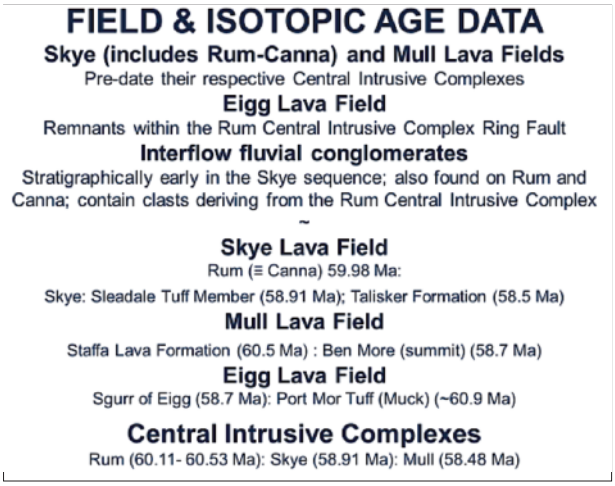

FIELD & ISOTOPIC AGE DATA
Skye (includes Rum-Canna) and Mull Lava Fields
Pre-date their respective Central Intrusive Complexes
Eigg Lava Field
Remnants within the Rum Central Intrusive Complex Ring Fault
Interflow fluvial conglomerates
Stratigraphically early in the Skye sequence; also found on Rum and Canna; contain clasts deriving from the Rum Central Intrusive Complex
~
Skye Lava Field
Rum (≡ Canna) 59.98 Ma:
Skye: Sleadale Tuff Member (58.91 Ma); Talisker Formation (58.5 Ma)
Mull Lava Field
Staffa Lava Formation (60.5 Ma) : Ben More (summit) (58.7 Ma)
Eigg Lava Field
Sgurr of Eigg (58.7 Ma): Port Mor Tuff (Muck) (~60.9 Ma)
Central Intrusive Complexes
Rum (60.11- 60.53 Ma): Skye (58.91 Ma): Mull (58.48 Ma)

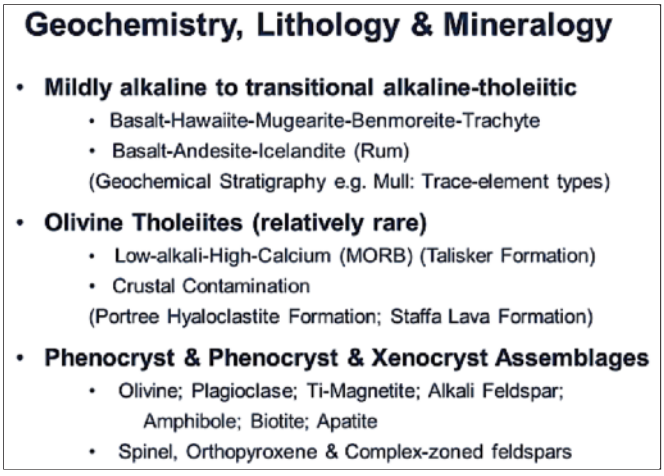
Figure 7 Age Relationships: table outlining the field and isotopic data for the relative ages of the Hebridean lava fields and associated intrusive complexes.

c. 60.7Ma, making it comparable to the Mull data. Also, the submarine outcrop of the lavas between Muck and north-west Mull shows an unequivocal link. The volcanic sequence on Eigg also includes the *c.* 120m 'pitchstone' of An Sgurr (the Sgurr of Eigg) (*c.* 58.7Ma). Recent research now classifies this as a rheomorphic, lava-like ignimbrite that infilled a river valley carved into the Eigg lavas, and may have been sourced from eruptions accompanying the emplacement the Skye Central Complex.

Lithology, geochemistry and petrography

In geochemical terms, most of the HIP lavas are mildly alkaline to transitional alkali-olivine basalts and their differentiates — hawaiite, mugearite, benmoreite and trachyte; the Skye field also had a few flows of picritic basalt, andesite and icelandite; and some basaltic units of the Mull field are distinguishable from one another based on trace element compositions. Lavas with olivine tholeiite compositions appear at the base of the Mull sequence (Staffa Lava Formation) and the top of the Skye sequence (Talisker Lava Formation). These distinctive units are not related, however, the former reflecting a significant degree of crustal contamination, and the latter a considerably increased partial melt of the residual mantle beneath the HIP (Fig. 8).

Figure 8 Hebridean Lavas: table outlining key elements of lithology, geochemistry, and primary mineralogy.


Geochemistry, Lithology & Mineralogy
• Mildly alkaline to transitional alkaline-tholeiitic
• Basalt-Hawaiite-Mugearite-Benmoreite-Trachyte
• Basalt-Andesite-Icelandite (Rum)
(Geochemical Stratigraphy e.g. Mull: Trace-element types)
• Olivine Tholeiites (relatively rare)
• Low-alkali-High-Calcium (MORB) (Talisker Formation)
• Crustal Contamination
(Portree Hyaloclastite Formation; Staffa Lava Formation)
• Phenocryst & Phenocryst & Xenocryst Assemblages
• Olivine; Plagioclase; Ti-Magnetite; Alkali Feldspar; Amphibole; Biotite; Apatite
• Spinel, Orthopyroxene & Complex-zoned feldspars

Overall, the range of compositions shown by these rocks reflects the combined effects of variable degrees of partial melting acting upon already, and variably, depleted spinel-bearing lherzolite upper mantle, along with complex magma ascent histories. As they ascended through the crust, individual melt fractions did so at different rates and by a variety of pathways. While some reached the surface with little interruption, others became temporally trapped within a plexus of intra-crustal magma chambers, with prolonged residence times promoting fractionation and crustal assimilation before eventual eruption. Inter-field differences in trace element and in rare-earth element compositions and isotope signatures are considered most likely to reflect lateral heterogeneity in the underlying mantle. Staying with the mantle, the HIP lavas have lower incompatible trace-element content compared to classical continental flood lava sequences worldwide and this is thought to be due to depletion of the mantle source beneath north-west Scotland during magmatism in the Permian.

Most of the basaltic rocks have a simple mineralogy of olivine, plagioclase feldspar, clinopyroxene and titanomagnetite. Only olivine and feldspar are present as major phenocrysts in the transitional-alkaline series, whereas pyroxene also occurs in the more tholeiitic types. In the more intermediate rocks these phases and titanomagnetite may be present as microphenocrysts. The most evolved compositions, the trachytes, carry phenocrysts of alkali feldspar with rare amphibole and apatite. Finer grain size and a marked flow alignment of groundmass feldspar are characteristics of the intermediate and evolved compositions. Secondary minerals are ubiquitous, and these include feldspathoids, calcite, quartz and a range of zeolites. These phases, deposited in gas cavities from circulating hydrothermal solutions, are temperature-sensitive and this has resulted in a zonation related to their depth of burial. Geothermometry studies suggest that at least 1km of lava has been eroded from the lava sequences. They are also sensitive to later thermal effects; and these effects have resulted in thermal aureoles around the intrusive complexes characterised by different zeolite species. Many enthusiasts collect these often-delicate minerals.

Stratigraphy

The lava fields comprise generally flat-lying, thick stratiform sequences (more than 1,200m) of fissure-fed, predominantly subaerial, geochemically transitional basalts, hawaiites, mugearites and trachytes. The more evolved lavas make up 10–15% overall and appear to be more prevalent at higher stratigraphical levels. There are also minor accumulations of subaqueous hyaloclastites and pillowed lava, rare pyroclastic flows (ignimbrites) and tuffs. Interbedded with these at the local level are thin, sedimentary deposits of various types. Detailed field mapping, section logging and follow-up geochemistry have enabled stratigraphical subdivision of both the Skye and Mull fields.

The presence of sedimentary sequences and palaeosols tells us that effusive activity was not a constant in the landscape, but was punctuated by protracted periods of volcanic quiescence. Ongoing field-based research on the sedimentary units and on the lavas bracketing them has recognised several distinct facies and facies associations in both volcanic and the sedimentary sequences. This research provides increasing and meaningful insight into the evolution of the lava fields and of the palaeogeography of the time. Interaction between volcanic and sedimentary systems also produced some intriguing rock types and features.

Volcanism and sedimentation

To best illustrate some of the key features and styles of volcanism and sedimentation, examples are chosen from three field-based case studies: the Staffa Lava Formation (Mull), the Talisker Lava Formation (Skye) and the Canna Lava Formation (Skye).

The lavas

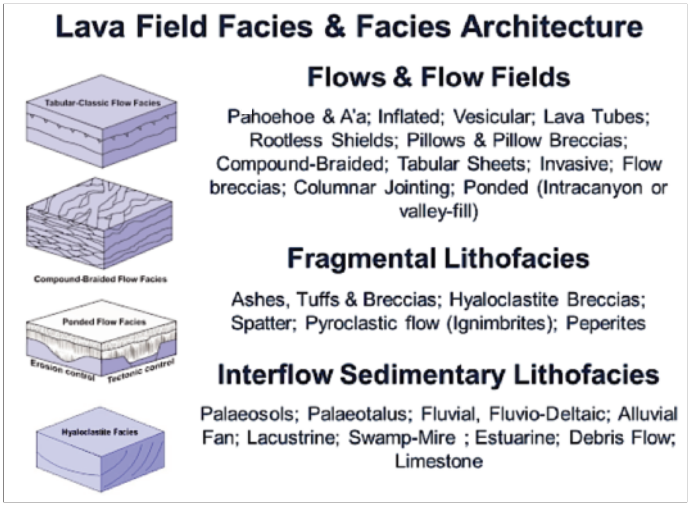
In the wind and rain, standing before the spectacular sea cliffs of the Hebrides, confronted by what at first sight appears to be a wall of intractable, black basalt, it is difficult to imagine the volcanological processes and dynamic landscapes that such sequences represent. Many of the morphological and medium-scale features commonly observed in lavas on recent and active basaltic volcanoes, such as pahoehoe structure, lava tubes, tumuli, etc, prove either elusive or difficult to interpret in ancient sequences. In this respect the lavas of the HIP are no exception, and until recently there were few published examples other than the presence of near-ubiquitous vesicular-amygdaloidal features.

Flow fields, facies and facies architecture

The thick sequences of lavas, so well exposed in the sea cliffs of western Mull and Skye, and along the Trotternish escarpment of northern Skye, show us that the lava fields were built-up through the superposition of a large numbers of coherent individual flows and more complex flow fields. A flow field may be described as a combination of the area occupied by, and the products of, a single, sustained eruptive event. Each event comprises a collection of stacked, inter-digitating or juxtaposed simple or compound flows and sheet-like flow lobes that are spatially contiguous.

The detailed form they take is controlled by a combination of intrinsic and environmental factors. Hence, lavas and flow fields may be treated in similar fashion to sedimentary rocks by describing them in terms of term 'facies' reflecting particular emplacement (depositional) processes and environments. Important factors include magma composition, eruptive volume, temperature, viscosity and effusion rate, and how each 'flow' interacted with the pre-existing landscape. Key elements in the landscape are variations in palaeoslope and either small- or large-scale irregularities in topography, such as the presence of channels between earlier lavas, major valley systems, and the presence (or absence) of significant water bodies.

Figure 9 Hebridean Lava Fields facies and facies architecture: diagrammatic representation of the principal facies types.


Lava Field Facies & Facies Architecture
Flows & Flow Fields
Pahoehoe & A'a; Inflated; Vesicular; Lava Tubes; Rootless Shields; Pillows & Pillow Breccias; Compound-Braided; Tabular Sheets; Invasive; Flow breccias; Columnar Jointing; Ponded (Intracanyon or valley-fill)
Fragmental Lithofacies
Ashes, Tuffs & Breccias; Hyaloclastite Breccias; Spatter; Pyroclastic flow (Ignimbrites); Peperites
Interflow Sedimentary Lithofacies
Palaeosols; Palaeotalus; Fluvial, Fluvio-Deltaic; Alluvial Fan; Lacustrine; Swamp-Mire ; Estuarine; Debris Flow; Limestone
Tabular-Classic Flow Facies
Compound-Braided Flow Facies
Ponded Flow Facies
Erosion control
Tectonic control
Hyaloclastite Facies

Each flow or flow field therefore has a distinctive morphology, and this is expressed as its 'facies architecture' (Fig. 9). Five principal types are recognised: (1) classical tabular, (2) compound-braided, (3) ponded or valley-fill, (4) hyaloclasite-pillow complex and (5) invasive; and there are excellent examples of each of these forms within the HIP.

Facies architecture types

As their name implies, classical tabular lavas are flat-topped and flat-bottomed, slab-like units. These are easily spotted in an exposed vertical sequence of lavas, as they are uniform, usually thick units traceable by eye over considerable distances, and inland commonly form strong terraces and escarpments. They represent relatively voluminous eruptions and are emplaced across a wide area (Fig. 10).

Figure 10 Tabular Facies Lavas: classical terrace ('trap') featuring on the Ardmeanach Peninsula, south-west Mull.

Compound-braided facies result where a lava or flow field is emplaced as a series of channelled, bifurcating and often anastomosing units. What is seen in section depends on where that section lies relative to the direction of flow and, as such, is therefore strongly related to the local palaeoslope. Cross sections parallel or near-parallel to the palaeoslope will tend to present as a series of thin, often seemingly disconnected, lenticular bodies occupying the same 'horizon', and typically with low aspect ratios. The same bodies seen in increasingly longitudinal sections will have higher ratios; the ultimate result would be a thinnish tabular flow. Good examples of these two facies types are seen in sequences exposed in the sea cliff sections of south-western Mull (Fig. 11, *opposite*) and western Skye and, inland also on Skye, along the Trotternish escarpment and hills such as Ben Scaalan (Fig. 12, *opposite*).

As liquids, lavas naturally infill depressions and so, in a sense, become 'ponded' within their local context. However, the ponded or valley-fill facies, as defined here, forms where lava completely infills and becomes impounded to a considerable depth within a major depression on the lava field such as a restricted valley or steep-sided gorge. To achieve this, the lava must be voluminous, of low relative viscosity and have a high effusion rate so that emplacement is rapid, and cooling is retarded until the flow comes to rest. Because the lava pond then remains static, and is not disrupted by later flows its interior cools slowly, and as it does so, suites of columnar joints form. Propagating perpendicular to primary cooling surfaces, these joints help define the position of the original confining valley (Figs 13–15, *opposite*).

The best and most spectacular example is the Talisker Lava Formation on Skye. What originally formed as lava that infilled

Figure 11 (top left) Braided Facies Lavas: lenticular and pod-like units at Bidean na h-Iolaire, Ardmeanach, south-west Mull; also present are tabular facies lavas in the middle and upper sections of the cliff.

Figure 12 (middle left above) Braided Facies Lavas: pahoehoe flows with thin inflation units overlain by a braided facies flow consisting of two unconnected lava lobes (in the plane of the photograph). The upper cliff comprises a tabular facies hawaiitic lava — Ben Scaalan, west Skye.

Figure 13 (middle left below) The Staffa lava flow: classical two-tier columnar joints sets, Staffa. The lava overlies a thick, bedded hyaloclastite unit. The same unit is exposed on the mainland of Mull, bellow the MacCulloch's Tree lava.

Figure 14 (bottom left) Multiple units of the Staffa lava: part of the Staffa lava flow-field. Each unit has its own suite of sets of columnar joints; a hyaloclastite unit is exposed below the lavas.

Figure 15 (top right) Ponded Facies Lavas: the 120m thick Talisker Lava at Preshal More (illustrated) and Preshal Beg in west Skye is an excellent example of a ponded 'intra-canyon' flow-field. The outcrops are also a good example of inverted topography — what was once a valley, is now two isolated hills.

a valley to a depth of more than 120m is now represented by two erosional inselberg-like remnants, the less-resistant earlier lavas of the valley walls having eroded away preferentially. This is a classic example of topographic inversion. As long ago as the 1930s American geologists coined the name 'intracanyon flow' for lavas behaving in this way.

Hyaloclastite is a fragmental deposit composed of degraded volcanic glass created when lava encounters and reacts explosively with a body of water such a shallow sea, lake or river. Deposition commonly results in the formation of a minor delta-like mound or ridge, and as eruption continues lava cascades and flows more passively down the delta front disaggregating into pillows (Fig. 16, *overleaf*); interbedding produces a mixed facies.

The Portree Hyaloclastite Formation on Skye is the best example of this facies within the HIP, but is poorly exposed. Better-exposed examples are seen on Mull, occurring as members within the Staffa Lava Formation. The best developments are the unit exposed below the columnar-jointed lavas on Staffa (*see* Fig. 13) and at MacCulloch's Tree, and others along the sea cliffs west of Carsaig Bay.

Where subaerial lava encroaches upon and enters a contemporaneous sedimentary basin its momentum may be such that it burrows into or emplaces beneath unlithified sediment to form an

Figure 16 Pillow Facies Lavas: exposure at Port an Fhasgaidh, south-west Staffa. The pillows overlie bedded hyaloclastite beds.

Figure 17 Invasive Facies Lavas: a basal apophysis (dark) of the upper lava, intrudes interbedded paheohoe units and sediments at Tallabric, south-west Sanday.

invasive facies. Such flows manifest as transgressive sill-like bodies, often with irregular brecciated margins and associated peperites where magma and wet sediment have interacted (Fig. 17).

Partial invasive activity may also be noted where an apophysis of a flow forces its way into fractures in the underlying stratum or lava. A form of auto-intrusion results where a later pulse of magma from the same eruption event is emplaced beneath the solidified (and therefore cooler) surface of its earlier unit of the same flow; lava tubes are an example (Figs 18 and 19). Examples of invasive phenomena have been observed within the Talisker, Canna and Staffa Lava Formations. The best peperite is that at Carraig Mhor, near Carsaig in south-west Mull.

As with many things geological, rocks seldom behave in quite so ordered a fashion, and architectures may take transitional forms that overlap one another. Also, flow fields and large-volume flows may exhibit more than one facies type. The best example of this is the Staffa Lava Formation, which has features common to ponded, hyaloclastite-pillow, tabular and invasive architectures. The Talisker Lava Formation lava is another example, exhibiting both ponded and invasive characteristics; similarly, some units within the Canna Lava Formation. Where there is evidence of contemporaneous reworking, the hyaloclastite facies overlaps with the sedimentary deltaic facies type considered in a later section.

Flows — internal or medium-scale (physical) features

Otherwise unremarkable exposures of ancient lava are made more interesting and informative to the casual observer where they preserve some of the smaller-scale volcanic features commonly observed on present-day lava fields. They provide crucial insight into the style of volcanism and physical processes, but the post-burial preservation potential of many appears to be rather poor, and so they can prove to be somewhat elusive in the field. We are fortunate to have some excellent examples within the HIP.

Fragmental rocks are not as common in the lava sequences as one might expect. Examples include spatter rags, clinker-rubble and hyaloclastite breccias. Magma spatter comprises irregular fragments of highly fluid lava that have 'fountained' from a vent, landed while still molten and piling up, then deformed and become agglutinated or welded to one another (Fig. 20, *opposite*). Such vents need not be related to the main fissure system and may form wherever the pressures of trapped gases are high enough to explosively expel lava.

Figure 18 Invasive Facies Lavas: the Talisker Lava exposed along the south face of Preshal Beg, west Skye. The subhorizontal, sheeted invasive facies forms the upper half of the unit above the two-tier columnar unit of the main ponded facies flow.

Figure 19 Invasive Facies Lavas: exposures of the sheeted invasive facies on the summit of Preshal Beg, west Skye. Each sheet has a single chill zone, suggesting sequential intrusion. Crude hackly prismatic jointing also features.

Another type is a volcanic rubble or scoria. This comprises fragments of solidified, highly vesiculated, and generally very fine-grained lava. These are sometimes referred to as clinker or cinder. Though more commonly formed as ejecta during explosive volcanism, scoria may also form as a brecciated, frothy surface crust of some pahoehoe lavas.

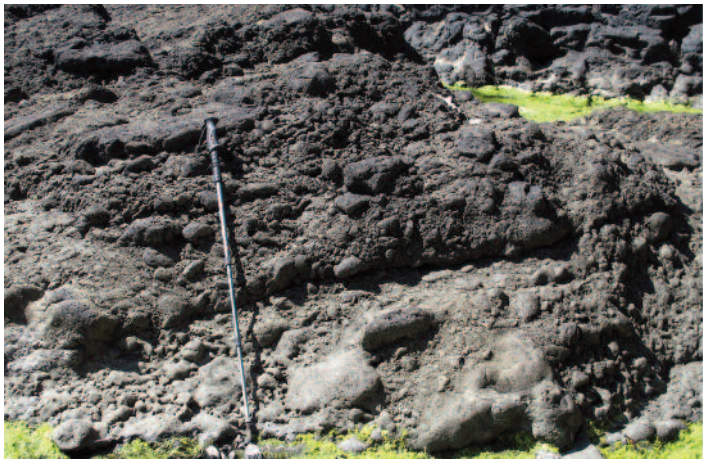
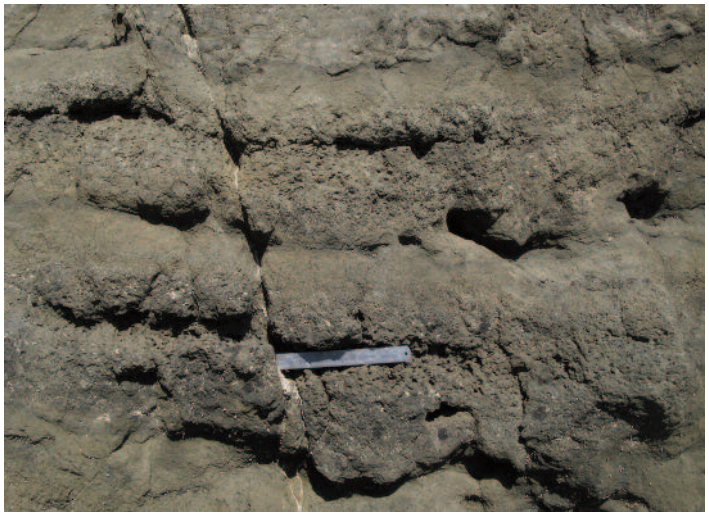


Figure 20 Fragmental Facies: lava rubble and spatter deposit, Canna Lava Formation, Cnoc Ghreannabric, Sanday.

Figure 21 Pahoehoe lobes at the base of the Dun Mor sea-stack, south-east Sanday. Note the chilled vesiculated margins.

Figure 22 Repeating inflationary pahoehoe sheets, Tallabric, south-west Sanday. Each sheet consists of a vesicular core and chilled margins.



Most of the HIP lavas appear to have been emplaced as pahoehoe flows, a feature of flood-basalt provinces in general. Features recorded to date include basal flow-lobes, stacked inflationary sheet structures and ropey surfaces. Relict lava tubes, mega-lobes and squeeze-up features have also been found (Figs 21–26).

(Fig. 26, *overleaf*).

Figure 23 Ropey lava: Carraig Mhor, south-west Mull.

Figure 24 Partially-filled lava tube, Quinish, north-west Mull.

Figure 25 Medium-scale lobes and small tubes forming a subfacies at the base of a thin tabular facies lava at Camas Thairbearnais, central north coast, Canna. The lava overlies a thick sedimentary unit.

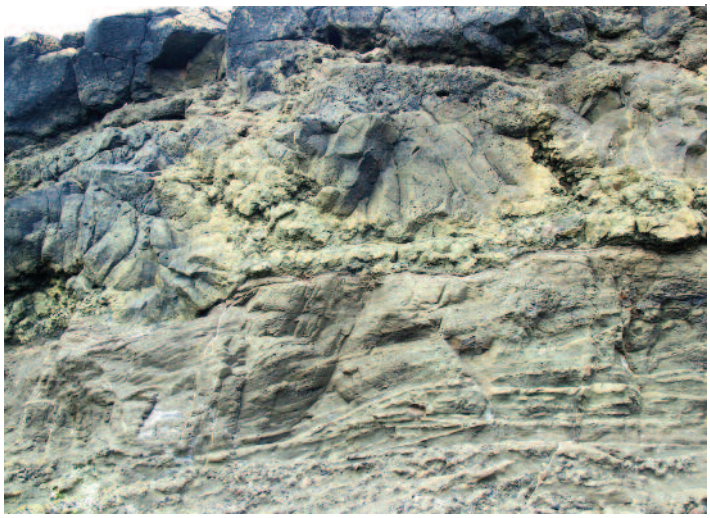


Figure 26 Lava-rise upwellings and lava blisters, Quinish, north-west Mull.

Amygdales (mineral-infilled gas vesicles) are almost ubiquitous and most prevalent in flow tops. They also become concentrated along flow-bases where lava has overridden wet sediment and vegetation. Rising streams of gas bubbles form and in some instances, may become deflected by a flow's continued movement; these are known as pipe vesicles. They may be used in a limited, local sense as indicators of flow direction. Larger, subvertical, possibly gas-vapour escape, spiracle-like structures are noted in some flows from the Staffa Lava Formation (Fig. 27). Formed in much the same way as pipe amygdales, a single gas-vapour column can form and attempt to bore its way to the surface, but may be arrested mid-flow. Should it breach the flow's surface, a minor phreatomagmatic eruption produces spatter that builds up as a small, so-called 'rootless cone'.

Figure 27 Spiracle-like structures arising from the base of a tabular facies flow, part of the Staffa Lava Formation, above Aird na h-Iolaire, south-west Mull.

Several lavas, especially those of mugearitic or trachytic composition, retain evidence of flow banding and folding. These features, generally observed as alternating bands of light and dark, or coarse- and fine-grained rock, reflect variations in opaque mineral content, degrees of crystallisation and complex alignments of flow-aligned groundmass minerals (Fig 28).

Sedimentation

Why include 'Sedimentation' in an article the focus of which is ancient lava fields?

Because, during their emplacement over the eons, both the Skye and Mull lava fields experienced prolonged periods of local and region-wide quiescence when volcanic activity, in any given area, either ceased or was severely curtailed. During such periods the processes of weathering, erosion, sedimentation and biotic recolonisation dominated the landscape. Sedimentation begins

Figure 28 Flow banding and folding in mugearite, MacFarlane's Rocks, north-west of Talisker Bay, west Skye.

Figure 29 Lateritic palaeosol developed on a rubbly-capped lava, Quinish, north-west Mull. The overlying Quinish Lava hosts a series of fossil tree moulds and casts.

the moment a lava stops moving and cools. This can start as the simple spalling and localised accumulation of fractured rock and loose debris, but given time and suitable climatic and topographic conditions (with no interruption from further volcanism), more complex and organised sedimentary systems and processes become established.

A considerable range of depositional environments and sedimentary lithofacies were created both on and peripheral to the HIP lava fields, and there is also considerable evidence that at times, volcanic and sedimentary 'systems' were active at the same time, frequently interacting with one another. Most of the HIP sedimentary sequences are localised and comparatively thin, but nevertheless, facies type, provenance, distribution and architecture combine to tell us a great deal about the geomorphological evolution of the lava fields.

Weathering and soils

In the moist, warm, temperate conditions of the time, and when there were sufficient intervals between eruptions, weathering profiles developed on the lavas, and soils formed. These are key to any palaeoenvironmental assessment and, by comparing them with modern soil formation processes, are a crude measure of formation time. Lithologically, most of these palaeosols are now beds of lateritic claystone, and easily spotted as they are reddish to purplish-brown in marked contrast to the dull greys of the lavas. They are a common feature in some formations, but are seldom more than a few centimetres thick. Some show evidence of reworking, but most are thought to have developed *in situ*, and there is often a transition from lava to reddened flow-top breccia to mature palaeosol (Fig. 29).

Some complex soil profiles contain beds resulting from the deep, *in situ* weathering of crystal and vitric tuffs, and wind-blown ash, providing key evidence for localised explosive volcanism during the construction of the lava fields; typical examples are those seen at An Dunan in northern Skye, Calgary Bay in north-west Mull and Port Mor on Muck.

Sedimentary units

The Staffa, Canna and Talisker Lava Formations provide excellent examples of sedimentary rocks interbedded with the lavas; these represent a range of depositional processes and environments.

Many sedimentary units are siliciclastic rather than volcaniclastic, comprise epiclastic clasts and grains, and have what might be broadly termed 'fluvial' characteristics. Indeed, purely volcaniclastic examples are comparatively, and surprisingly, rare. Typical lithofacies include coarse, unsorted boulder conglomerates deposited under debris flow and hyperconcentrated flow regimes, channelised and sheet-flood and stream-flow conglomerates, pebbly sandstones, and a spectrum of stream-flow sandstones and siltstones (Fig 30).

Depositional environments for the coarser-grained lithologies included alluvial fans and braided outwash plains, meandering river channels and ephemeral flash flood streams. Organised associations of siltstone, claystone and coal are interpreted to represent riparian overbank, waning flow, and the transition to channel abandonment, lacustrine and mire conditions. Some beds from the Staffa Lava Formation formed under localised estuarine, or at least more saline, conditions.

Coastal exposures on the small island of Sanday — off Canna in the Small Isles — are one of the best places to study these features. An impressive example of a debris-hyperconcentrated flow conglomerate is exposed at the base of the sea stack of Dun Beag (Fig. 31, *overleaf*).

This is a chaotic, unstratified assemblage of boulder- to small pebble-grade clasts set within a variable sand- to granule-grade matrix. The size, and therefore mass, of the larger clasts could only have been transported under high energy conditions, and in a subaerial setting, typically those characterising an upper alluvial fan, flash flood, debris avalanche-type environment. Nearby cliffs show more organised beds of conglomerate with minor

Figure 30 Sedimentary Processes and Deposits: the construction of the Palaeocene lava fields involved both volcanism and sedimentation. Some of the best examples of the latter are those exposed on the south coast of Sanday. Shown here is the sea-stack of Dun Beag, which includes a channel-fill sequence and the channel margin, both overlain by a later flow. Rum is in the background.

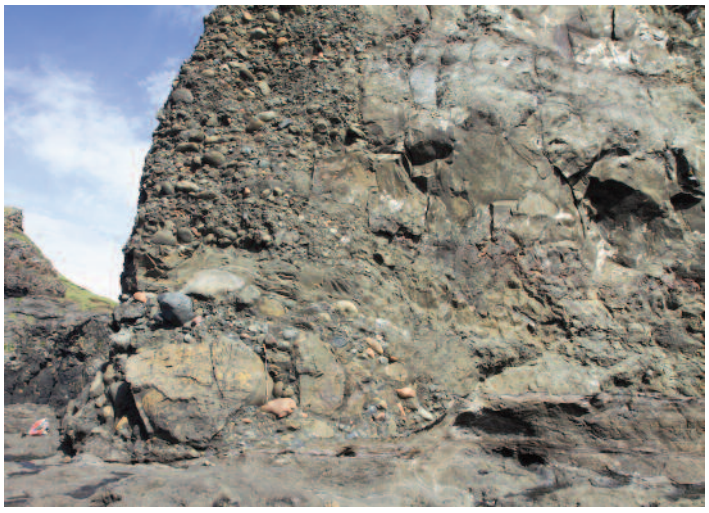


Figure 31 Sedimentary units at the base of the Dun Beag sea-stack, south-east Sanday: left side, basal beds of laminated siltstone overlain in turn by coarse-grained debrite conglomerate, and a sandstone-conglomerate fluvial sequence; upper-right, the conglomerates infilled a steep-sided channel in the lava sequence.

sandstones with cross-bedding and both fining-upwards and coarsening-upwards profiles. These are typical of wide-based channelised bodies and minor deltaic-like flash flood splays. Clasts in all these conglomerates vary from angular to rounded and comprise locally derived basalts and hawaiites, reddish feldspathic sandstone derived from the Torridonian Supergroup and a small but highly significant suite of intrusive igneous rock sourced from units within the Rum Central Intrusive Complex.

The only major volcaniclastic sedimentary unit is the sequence of reworked hyaloclastite tuffs and tuffaceous sandstones underlying the renowned columnar-jointed lava on Staffa and it equivalents on the mainland of Mull. Associated with pillow lavas and showing graded-, cross- and surge-bedding, this is thought to represent deposition in a shallow deltaic environment on the margins of a major lake. Emergent surfaces include volcanic spatter, quenched magma rags and large, carbonised wood fragments. In western Sanday there are other examples of 'volcaniclastic' units, where clast content is entirely of localised lava field lithologies (lavas, palaeosols, etc). At Tallabric, sediment of this type was seemingly washed into a series of the lenticle-shaped inflation voids within the upper crust of the underlying pahoehoe flow; no two void-fills are identical.

Perhaps the best example of a fluvial channel infill sequence is that of the Pulpit Rock on the south-west coast of Mull (Fig. 32).

The Rock itself exhibits two types of conglomerate. Overlying a basaltic lava towards the base is a thin debrite composed solely of subrounded boulder-cobble clasts of the local basalt lavas, and above this is a thick unit of finer-grained conglomerate comprising clasts of Upper Cretaceous flint and indurated chalk (Fig. 33, *opposite*). Adjacent cliffs also expose the debrite, but the channel conglomerate is absent, having been replaced by a fining-upwards sequence that culminates in coaly mudstone. The entire sequence records either the infilling of a fluvial channel and its abandonment or a steep-sided fluvial channel incised into more stratified beds. Another example of a channel conglomerate sequence is seen in association with the Ardtun Leaf Beds, famous for their preservation of Palaeocene plants. These conglomerates and coarse-grained pebbly sandstones also carry flints and indurated chalk clasts, but in this case, represent a series of minor anastomosing channels on an alluvial braid plain.

Carbonaceous claystones and poor-quality coals are common, but are generally thin and much restricted in lateral extent. However, in the past, some were of sufficient quality to be worked locally. The best examples are those situated along the south-west coast of Mull. There are also rare examples of limestone or calcareous siltstone. Most are thought to be localised, diagenetic effects, but one example, again from the Staffa Lava Formation, is unusual as it comprises sub-rounded grains of calcite with subsidiary quartz, feldspar and magnetite. This material appears to be detrital and to have been derived by mechanical weathering without the typical dissolution weathering of a cemented carbonate source rock. Deposition is thought most likely to have been in small freshwater pools on the lava field with a low influx of terrigenous sediment.

Figure 32 Fluvial channel conglomerate in the Staffa Lava Formation, Pulpit Rock, south-west Mull. The conglomerate shows cross-bedding and comprises mainly flint and indurated chalk clasts. Remanie Upper Cretaceous Chalk beds occur on Mull, but none are exposed in the vicinity.

Sedimentation was seldom, if ever, on a fully basin-wide scale. For the most part it was confined to the local, shallow valley systems and those marginal zones that developed between the lava fields and bordering higher terrain, for instance, the uplifted axis of contemporaneous fissure systems or adjacent hinterlands of older rock such as the edifice of the eroding Rum volcano.

Wasting of the lava fields

Other than in a few isolated, shallow pockets observed between some lavas, there is comparatively little evidence of significant erosion, transport and deposition of locally derived volcaniclastic sediment. The down-wasting of the lava fields on any appreciable scale occurred only late in their history. Two examples, the Preshal Beg

Figure 33 West of the Pulpit Rock, south-west Mull. This exposure, between two Staffa Lava Formation flows shows a classic abandonment fining-upwards motif of debrite with basalt and flint clasts, overlain, in turn, by conglomerate, pebbly sandstone, siltstone, silt mudstone and coal.

Conglomerate Formation on Skye and the Ben Hiant and Achateny Breccia Members in Ardnamurchan serve as examples.

Mainly as a series of overlapping lobes of coarse, unstructured debrite, the Preshal Beg Conglomerate floored a graben-valley developed on the late Skye lava field. Clasts are mostly subrounded and derive solely from the eroding lava field (Fig. 34). Both the conglomerate and the Talisker Lava Formation that followed were emplaced several kilometres downslope from the developing Cuillin shield volcano. The formation includes a breccia facies, interpreted as a palaeotalus deposit at the foot of the valley walls.

Figure 34 Preshal Beg Conglomerate Formation, Preshal Beg, west Skye. A debrite comprising granule to block-grade clasts of basalt, hawaiite and mugearite derived from the weathering and erosion of the subjacent lava field.

The Ardnamurchan breccia members represent the redistributed products of deep weathering and wasting of the Mull lava field and underlying pre-Palaeogene rocks; they predate the formation of the Ardnamurchan Intrusive Complex and comprise a series of laterally discontinuous, alternating, fine and coarse clastic units of coarse breccia, bedded conglomerate, pebbly sandstone, sandstone and siltstone. The Achateny Breccia includes large clasts or mega blocks of both volcanic and country rock, some measuring tens of metres across (Fig. 35, *overleaf*).

Interaction between volcanic and sedimentary systems

Interactions between concurrent volcanism and sedimentation were either direct or indirect. They occurred on a variety of scales, from the regional to the purely local.

An example of interaction at the regional scale is that observed between the early Skye lavas in west-central Skye and Rum, and the sedimentary units of the Canna Lava Formation. Within the Skye Lava Group there are numerous, mainly thin, inter-lava sedimentary units. Those early in the sequence (Minginish Conglomerate Formation and Canna Lava Formation) include significant fluvial sandstone-conglomerate units that are considered broadly coeval. Other than locally derived volcanics, clast assemblages on Skye are dominated by pink arkosic sandstones (Torridonian) with a small population of granophyric granite and felsite. The Rum and Canna assemblages carry more local volcanic debris, but also include clasts from the underlying country rocks (Lewisian gneiss and Torridonian sandstone) and, crucially, some matching lithologies found within the Rum Central Complex (granite, granophyric granite, and microgranite, rhyodacite, gabbro troctolite).

The presence of these igneous rocks in the conglomerates on Rum, Canna and Skye tells us that the Rum Complex had been unroofed and was undergoing active erosion by the time the Skye lava field was forming. Though complicated by local factors, a broadly northerly transport direction is implied. Accepting that most lavas erupted from fissure systems — evidenced by the Regional Dyke Swarms — and if emplacement resulted in uplift along the swarm's axis, overall lava flow in the Skye-Canna-Rum area ought to have come mainly from the north to north-east. There are comparatively few dykes on Canna-Sanday and consequently little evidence of fissures and localised uplift that might have contributed to lava-flow in the opposite direction. This presents an obvious conflict — sediment transport *to* the 'north', but lava-flow *from* the 'north' (Fig. 36, *overleaf*).

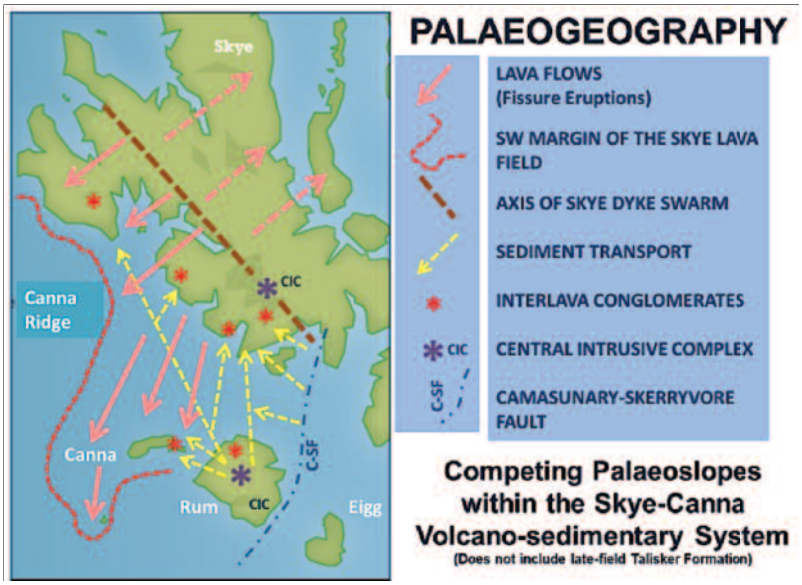
During the early development of the lava field these palaeoslopes clearly interacted and alternated. It is possible to reconcile this by suggesting that a shallow, broad basin undergoing

Figure 35 A mega-block within the Achateny Breccia, north Ardnamurchan. This rotated clast comprises well-bedded Jurassic sandstone and measures over 25m in diameter; is was probably deposited as a debris-avalanche.

intermittent subsidence existed between what is now Skye and Canna, with the high ground of the eroding Rum volcano to the south and internal highs formed near fissures systems towards Skye. Sediment was shed from Rum and transported north and north-north-west along a system of river valleys and plains, which were periodically dammed or obliterated by fissure eruptions from the north. Continued subsidence without volcanism then allowed the temporary re-establishment of the north-directed palaeoslope before this was overwhelmed by increasingly frequent lavas as the lava field became fully established.

At the medial scale, the build-up of new flow fields created uplift and new landscapes, and their architectures dictated, for example, the courses of channels and basins that, on occasion, infilled with sediment only to be buried by subsequent lavas. Later flows blocked active and ephemeral fluvial channels, creating lava dams and causing sediment to accumulate upstream. Catastrophic breaching of these dams is thought to be a possible driving mechanism behind some of the debrites and hyperconcentrated-flow conglomeratic beds described earlier.

Figure 36 Palaeocene Palaeogeography: there is clear indication that volcanic and sedimentary systems and processes interacted with one another on the regional scale. However, some of the data presents an enigma — one of conflicting Palaeoslopes and provenance.



Further evidence of direct interaction between lava and sediment takes the form of shallow invasive or intrusive tongues and lobes of lava. Where highly fluid magma encounters and mingles with unlithified, water-saturated sediment, it disintegrates or fragments, forming an unusual rock known as 'peperite'. A particularly fine example crops out at Carraig Mhor, in south-west Mull (Fig. 37, *opposite*). It comprises altered, pale brown-green igneous clasts of basalt with sub-angular through sub-rounded to curvilinear and crenulate fluidal morphologies. Some clasts are fractured, with irregular margins commonly displaying a jigsaw fit, contrasting with the 'bulbous' and 'finger-like' projections of others. Most clasts are of highly altered, semi-glassy igneous material; some have well developed vesicular and quench-textured rims. Clasts are enclosed in a dark grey, finely laminated matrix of carbonaceous, silt and clay. Laminae are defined by grain size and colour contrasts, and are typically contorted and concordant with clast margins. The matrix also fills late-stage fractures that have penetrated some clasts.

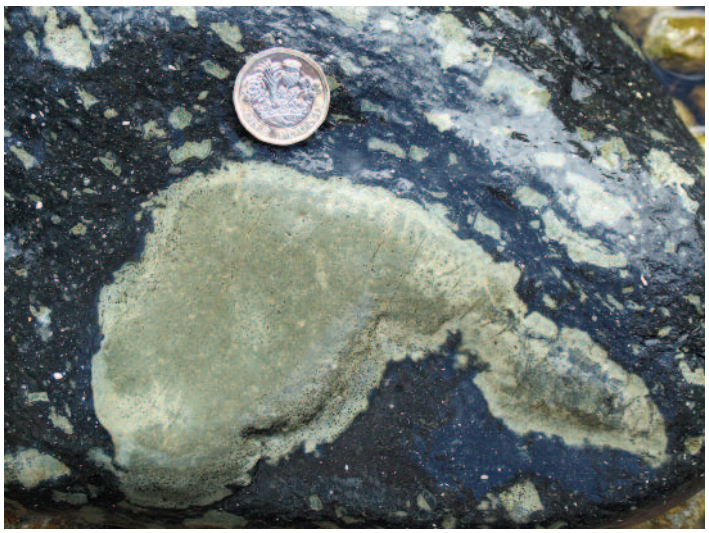


Figure 37 Peperite: ragged, chilled clasts (pale) of once highly fluidic basalt lava within a turbulent matrix of coaly mudstone, Carraig Mhor, sout-west Mull. Such features are indicative of liquid-liquid contacts involving magma and over-saturated sediment.

Another effect is the loading imposed on unconsolidated sediments by massive flows as they advance over them. This can induce shearing and slumping folds in the sedimentary sequence. Good examples of both phenomena are seen in sections on the small island of Sanday, off Canna (Fig. 38).

The wider nature of volcanism may have altered unconsolidated or poorly lithified sediments in less direct ways. For example, a bed in the Canna Lava Formation on Sanday (Fig. 39) consists of widely scattered granule- to pebble-grade lithic clasts within, and supported by, an unsorted, mud-silt-sand (i.e. 'muddy' matrix). It is homogenous, with no laminae or grading. Such a bed may be interpreted in several ways. It may be nothing more than a simple subaerial mudflow (slurry deposit), perhaps the distal deposit of a debris flow, or it may be a shallow-water turbidite.

But there is another possibility. Seismic activity goes hand-in-hand with volcanism, and it is possible that this particular bed is a 'seismite', the result of seismically induced thixotrophy and the liquefaction and remobilisation of water-saturated sediment and unlithified beds. Nearby exposures of the same bed provide

Figure 39 Unstructured bed comprising a population of small lithic clasts freely 'floating' within a silty mud matrix. Interbedded with more structured beds, this bed may have formed from the fluidisation and homogenisation of existing water-saturated beds. If this process was induced by earthquakes, this bed qualifies as a 'seismite'.

Figure 38 Sedimentary unit at Camas Thairbearnais, Canna showing evidence of volcanically induced loading, slumping and shearing, and incipient fluidisation.

supporting evidence, for they include a thin 'sandstone' capping. The capping appears to have been only partially lithified at the time and to have ruptured contemporaneously with the emplacement of the overlying lava. A mobilised 'pebbly mud' penetrated the spaces between fragments of fractured crust from below; and the base of the overlying lava developed peperite above the breach.

Remobilisation of water-saturated sediment also explains the apparent injection of 'flames' of clastic sediment upwards into the base of a lava in south-west Mull (Fig.40).

Fossils and palaeoecosystems

Although they were hostile environments, the lava fields were seldom completely barren landscapes devoid of life. The presence of fossils in some sedimentary formations is clear evidence

Figure 40 Lava-Sediment Interaction: fluidised bed of calcareous sandstone rising as a series of flame structures through the base of a Staffa Lava Formation flow, west Traigh Cadh' an Easa, south-west Mull.

that quiescent, ameliorating conditions between eruptions periodically lasted long enough to enable living communities to establish and develop. Though limited, such remains present tantalising clues about ecosystems, conditions and processes operating on and adjacent to the lava fields.

During the mid-Palaeocene north-west Scotland lay farther north than it does today, and was part of a major biome — polar broad-leaved deciduous forest. Early Palaeogene high-Arctic forest ecosystems have no modern equivalents; today, no significant deciduous forest ecosystems exist at such high latitudes. While mature forest likely prevailed on the surrounding highlands, the lava fields were, for the most part, only ever partially vegetated. Isolated patches of vegetation surrounded by barren lava acted as living 'seedbanks', facilitating colonisation of fresh surfaces. These isolated refugia worlds have the wonderfully evocative Hawaiian name, *kīpuka* (Fig. 41).

*Figure 41 Refugium (*kīpuka*), Hawaii: when a braided facies flow encounters established ecosystems on variable topography it encircles all but the highest terrain, leaving islands of life that serve as seed-banks for the eventual colonisation of the new lava surface.*

Post-eruptive landscapes therefore would have comprised a mosaic of overlapping zones exhibiting various degrees of disturbance and recovery. Floras preserved in sediments represent seral vegetation in varying stages of recovery from volcanism, fire and hydrologic disturbance. While carbonised and comminuted plant remains are relatively common, they tell us comparatively little. Luckily, the HIP hosts the internationally important Ardtun Leaf Beds, a better preserved and hence more informative fossil assemblage.

The Ardtun Leaf Beds (Staffa Lava Formation) were laid down as a series of conglomerates and sandstones, and abandonment lacustrine-mire silty mudstones, in a predominantly braided fluvial setting. The finer lithologies preserve diverse leaf macroflora and palynoflora, an assemblage that indicates a mid-successional tree-fern and Ginkgo-dominated scrub community with rare beeches, oaks and myrtle-like shrubs and trees. There are also 'lower' plants such as various ferns, horsetails, mosses and liverworts. Palynological studies made across the wider Staffa Lava Formation confirm the presence not only of temperate species such as redwood, fir, spruce, pine, yew, oak, willow, alder, plane, hazel and other species, but also more exotic and 'thermophilic' plants such as palms, cashews, walnuts, hickory and maidenhairs, together with club mosses, tree ferns and associated lianas. Combined, this assemblage makes the Ardtun site, with its predominance of deciduous trees growing in a disturbed volcanic landscape, unique within the UK; and renders it crucial to the wider understanding of plant migration and floristic evolution of Europe during the early Palaeogene. Leaf remains have also been found in units of the Skye lava field.

But not all fossils are found within sedimentary rocks. Forests and tree stands of various sizes became established on many parts of the lava fields, but they were always going to be under threat and intrinsic environmental stress. Trees can be either rapidly consumed by advancing flows or be more resistant and later burned away, their forms only preserved as moulds and casts within solidified basalt. Such trace fossils are increasingly rare the older the geological record, but on Mull we have good examples, making them among the oldest known worldwide.

An example is 'Macculloch's Tree', an upright fossil tree *c.* 12m × 1.5m encased by columnar basalt in the Staffa Lava Formation (Fig. 42). The manner of its preservation within lava rather than

Figure 42 MacCulloch's Tree: a 12m upright cast and mould of a conifer tree that was submerged by lava, Burg coast, south-west Mull. Preserved material includes mineralised woody tissue and charcoal. The engulfing lava ponded and cooled slowly, forming the sets of columnar joints perpendicular to the cooling surfaces presented by the tree.

Figure 43 The Quinish Tree, north-west Mull: a cylinder 'fossil' of basalt. A fallen tree was engulfed by lava and consumed. The lava solidified leaving a void (mould), which was subsequently infilled by magma.

sediment, upright posture, size and age render it exceptional and one of only a few discovered to date, worldwide. Its upright posture has always been taken as evidence that it was fossilised *in situ*, but there are issues with this interpretation: there is no discernible root system; and its intact preservation, partially as a cast of mineralised woody tissue and charcoal, suggests that it was already dead, waterlogged and sheared from its base before burial. Discovered by John Macculloch sometime between 1811 and 1815, its exact identity remains uncertain, but it is generally considered a conifer. The original geological survey of the area confidently asserted that it was a conifer of the fossil genus *Cupressinoxylon*, a view consistent with an earlier study stating that there was no significant difference between *Cupressinoxylon* and *Taxodioxylon*. Associated sediments carry a palynoflora dominated by a taxon derived from swamp cypresses and *Metasequoia* (*Inaperturopollenites hiatus* — in the cypress family), which suggests that the tree, on balance, has affinities to *Taxodioxylon* (Taxodiaceae conifers).

Another key site is at Quinish in north-west Mull. Here there is evidence that despite being under threat and suffering intrinsic environmental stress, a small stand of trees established itself on the lava field. There are 20 specimens of preserved moulds and casts across the site, the largest of which is a prostrate trunk preserved as a cast of basalt (*c.* 4.3m × 0.65m) (Fig. 43). Their orientation is mainly orthogonal to the trend of the Regional Mull Dyke Swarm, probably indicating that the inundating lava flowed west-south-west away from its source fissure and down the prevailing palaeoslope, at least locally (Fig. 44).

Figure 44 Quinish Fossil Trees: moulds and casts of some 20 trees have been found in a lava flow at Quinish in nortrh-west Mull. Measurements confirm a preferred orientation that might indicate local flow direction.

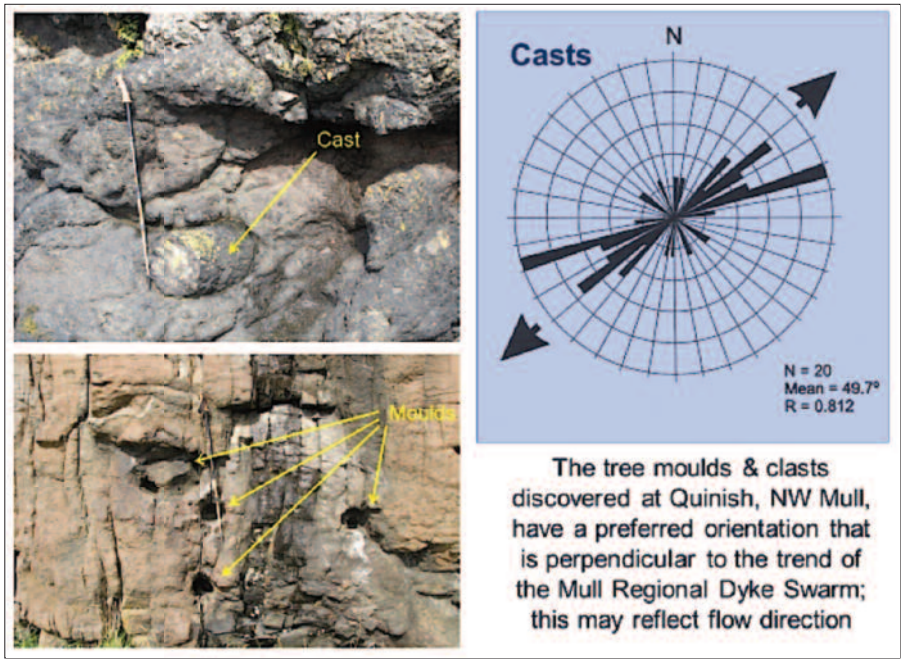
In contrast, faunal life on the lava fields has received little attention. Finds are rare, and the available data come from research on the Ardtun beds in the 1930s and 1940s, but is relevant to the entire HIP. No comprehensive palaeoecological or environmental synthesis has been attempted. The beds yielded few faunal fossils, dominated by invertebrates — mainly insects, and some molluscs (Fig. 45, *overleaf*). A site west of Carsaig Bay has also been discovered to contain fragments of ostracods and fish bones. Not only does this eclectic fossil assemblage hint at the complexity of the ecosystems of the time, but it also sheds light on environmental conditions. For example, species living in water for some or all of their life cycles — such as riffle beetles, river limpets, and dragonflies and caddis flies — provide clues of oxygenation levels, flow rates, substrate conditions and likely depositional environments; growth rings on molluscs provide crude estimates of the duration of the inter-lava time interval. Similarly, terrestrial insects such as ground beetles, crane flies, bark beetles, march flies and weevils are evidence of life in the trees and on forest floors. With imagination we can even speculate about the colours and sounds of the Palaeocene world; forests full of cicadas and crickets would have been noisy places.

Reconstructing ecosystems and landscapes

To gain meaningful insight as to the landscapes of the time and of the ecosystems they supported, a combination of all available volcanological, sedimentological and palaeontological data is needed.

Ecosystems

Reconstructing palaeoecosystems is challenging, especially those associated with ancient volcanoes, and with only limited palaeontological data, but is not impossible. Seldom were intervals between eruptions long enough, and environments suitable, to enable ecosystems to reach levels of complexity and maturity capable of supporting abundant, diverse life. Most intervals were short, favouring only ephemeral, early successional habitats colonised by pioneer plant species such as ferns and by scavenging animals. We can, nevertheless, speculate as to what the 'missing elements' were, and so consider likely community structure.


Cast
Casts
N
N = 20
Mean = 49.7°
R = 0.812
The tree moulds & clasts discovered at Quinish, NW Mull, have a preferred orientation that is perpendicular to the trend of the Mull Regional Dyke Swarm; this may reflect flow direction

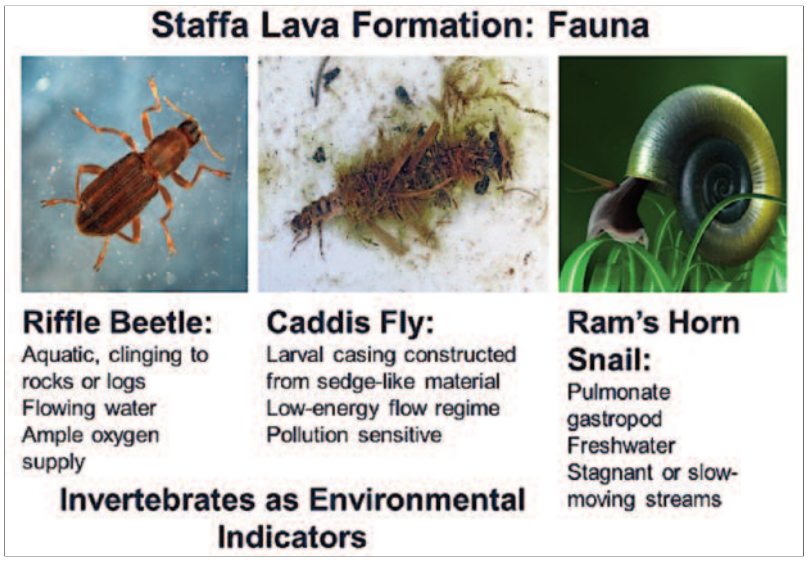


Figure 45 Environmental Indicators: (examples) the Ardtun Leaf Beds, a member in the Staffa Lava Formation, have yielded a small, but ecologically significant fauna.

Most of the data we have relate to plant communities. Once ecological succession had advanced beyond the early stages: riparian, lake margin and swamp habitats were the most common. These were populated by a range of deciduous and evergreen tree and shrubs, including beech, oak, plane, ginkgo and cypress, with understoreys of ferns and sub-canopy vines. These dominantly mid-successional plant communities reflect longer periods between eruptions. Away from immediate river channels, floras included diverse, angiosperm-rich wetland communities, some with epiphytic and understorey ferns typical of heavily vegetated swamps with standing water and shallower marginal peat swamps. Hinterland and marginal elevated areas were relatively free from volcanic disturbance and hosted true late-successional communities of *Metasequoia* (redwood pine) forest. Palynological analysis confirms the presence in some units of dinoflagellates cysts typical of open estuarine and mudflat environments.

Environmental reconstruction taking account of the fauna requires many assumptions. Most important are the basic rules that apply to modern ecosystems, enabling us to make educated guesses, assuming that the formation of guilds, predator-prey-scavenger relationships and successional pathways operating in past volcanic environments were similar to those in the present. Even with the sparse data we have for the HIP we can attempt to construct a rudimentary food-energy web, and tentatively fill in some of the missing elements by examining the fossil record of coeval deposits elsewhere within the biome, plus present-day analogues.

The first animal colonisers were probably airborne, in the form of aerial plankton. Through comparison with modern lava fields, these pioneers would include small spiders, ants, flies and wasps, and a range of opportunistic scavengers such as insects, arachnids, small reptiles, birds and small mammals preying on these pioneers and on each other. These terrestrial animals are rarely preserved, except occasionally in sediments flooring former crevasses and lava caves. With time, soils formed, bodies of standing water became a feature of the landscape and vegetational succession transformed the composition of ecosystems as biotic communities responded to and modified their environment.

Fossil evidence from across the biome indicates that climatic conditions were generally mesothermal to humid, largely frost-free and favoured a long growing season. However, growth shut down annually during a period of winter darkness, limiting diversity and habitat variation. With environmental stress brought by volcanism and shifting patterns of sedimentation, for example channel switching, biodiversity and variation would have been even more restricted. Populations in early-formed refugia would have faced many challenges, such as water and food availability, and a lack of habitat interconnectivity.

Palaeontologists speculate that these mid-Palaeocene forests were mainly populated by small terrestrial to semi-terrestrial animals, many of them tree-dwellers (Fig. 46). Rodents most likely dominated any mammalian fauna, although there may also have been early bat species. Ground-dwelling mammals probably included variously sized grazing herbivores. There were also varanid reptiles, including lizards, snakes and land tortoises. Lakes, ponds and marginal riverine environments included frogs and salamanders, turtles and freshwater (caiman-like) alligators.

The Palaeocene marks the beginning of a spectacular evolutionary divergence of bird groups, but as the fossil record from Europe is fragmentary, little is known about them. Most specimens come from aquatic (marine to estuary) or semi-aquatic species, and so are not readily comparable to the terrestrial setting of the HIP. If habitat and niche requirements were met, then there may have been small populations of ground-dwelling ratites, perhaps including the large rhea-like Gastornis. There were some early owl-like forms such as Berruornis, but small arboreal birds are conspicuously absent from the fossil record. Perching birds had not yet evolved, and so these fragmented Palaeocene forests may well have been bereft of bird song.

Figure 46 Phantom Ecosystems: a functioning ecosystem of the mid-Palaeocene would have included top-predator species. Fossil finds from the same biome at sites Europe and North America suggest a restricted range of primitive mammals and birds.

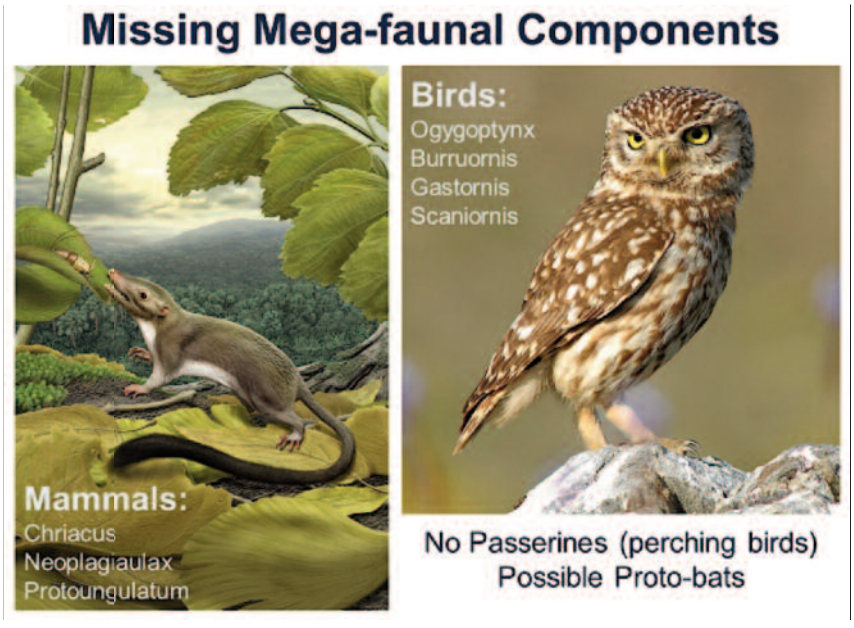


Figure 47 Representation of a landscape in Iceland that likely characterises the volcanic phases of the Palaeocene lava fields.

There is also some evidence for plant–animal interaction. Many of the plants identified are angiosperms and some were insect pollinated, the Ardtun fauna including, for example, nectar-feeding jewel beetles. There is also fossil evidence of insect herbivory. Leaf macrofossils of *Rhamnus major* (a type of buckthorn) from Ardtun include thin irregular linear features, and these are interpreted as probable grazing tails or mining traces left by insect larvae. These may have been jewel beetle larvae, but a study of similar features in leaves of coeval deposits from Spitzbergen (Svalbard) attributed them to the activity of leaf-mining moth caterpillars.

Lava field Landscapes

Formation of the lava fields of the HIP took place over *c.* 3Ma years. During most of that time, effusive, fissure-fed volcanism dominated, but there were also intervals of relative quiescence between eruptions. During these non-volcanic interludes, some more prolonged than others, there was weathering, erosion and sedimentation, and the return of life. Such disparate processes produced different landforms and features, and at any one time landscapes were likely complex mosaics.

Volcanic landscapes would have been dry, barren and rugged, and inhospitable to most forms of life. They were probably much like currently active volcanic fields on Hawaii and Iceland. Most topography would have been subdued, with intra-field palaeoslopes controlled by elevated zones developing along the axes of major fissure systems, and by local inter-flow-field irregularities (Fig. 47).

During periods when volcanism waned or became dormant, erosional and depositional processes dominated the landscape. We may imagine a landscape in which the high hinterlands continued to shed debris into gently subsiding basins in alluvial fans, ephemeral streams and flash flooding, followed by more mature river systems and lakes as these became established ever farther out into the dormant lava fields, and as life slowly returned — only to be obliterated by renewed volcanism. Such a scenario is illustrated by considering three examples from the HIP.

The Staffa Lava Formation on Mull developed within a fault-bounded topographically low landscape, with marginal (hinterland) uplands; the climate was warm-temperate to locally sub-tropical in sheltered spots. The preponderance of columnar-jointed facies lavas and hyaloclastite breccia indicates an abundance of standing water within this graben landscape, also reflected in the presence of several sedimentary members. During these periods of relative volcanic quiescence, the landscape was a complex mosaic of volcanic and fluvial, lacustrine, mire and estuarine environments.

By contrast, the sequences exemplified by the coastal sequences of the Skye Lava Group on Sanday are representative of more localised, ephemeral stream channels. Compared to the Staffa Lava Formation, a drier regime prevailed, with only intermittent, but seasonally heavy rainfall. The lava field was flanked to the south by the high ground of the extinct Rum central volcano. Down-wasting and deep incision produced a series of steep-sided ravines and gorges that enabled streams to deposit sediment-laden debris out onto the lava field (Fig. 48).

Uplift, significant wasting and deep incision occurred at a late-stage in the development of the Skye lava field and before the emplacement of the Talisker Lava Formation of the Skye Lava

Figure 48 An example of sedimentary, down-wasting landscape around Mt St Helens in Washington State, USA, the like of which might have characterised prolonged, volcanically-quiescent interludes.

Figure 49 Valley-fill lava, south Iceland: in terms of scale, volume and emplacement style, the fissure-driven Lakagígar (Laki) flow-field from the 1783–4 eruption is a good analogue for the Talisker Lava Formation, athough the climactic conditions were very different.

Group. A fault-bounded valley with talus-margined cliffs formed. Vigorous streams cut deep into earlier volcanic formations, delivering coarse sediment in high-energy debris flows that originated on the flanks of the developing Cuillin shield volcano. Ultimately, this entire canyon-like valley was buried to a depth of more than 120m by the Talisker lava (Fig. 49).

After the fires

After the demise of the Skye and Mull lava fields major central shield volcanoes erupted and subvolcanic plutonic processes emplaced intrusive complexes. This activity initiated uplift, edifice collapse, down-wasting and sedimentation. A particularly good example is the melange-style, mega-clast breccias on the remnants of the Mull lava field in eastern Ardnamurchan.

Little is known about the geological processes affecting the region during the rest of the Palaeogene. There was a short period of significant global warming in the early Eocene — the so-called Palaeocene–Eocene Temperature Maximum — but no definitive strata of this age are recorded from the HIP. Although conditions appear to have remained stable and mostly terrestrial, sustained uplift, deep weathering and vigorous erosion during the Oligocene (*c.* 34–23Ma) deposited *c.* 800m of sediments in the Canna Basin, south-west of Skye, and *c.* 1,000m in the Little Minch. It is generally assumed that during the Neogene (Miocene and Pliocene: *c.* 23–2.5Ma) the former volcanoes, on land, were buried beneath thick sequences of vegetated and deeply chemically weathered bedrock and regolith. Tectonically the region was relatively calm, although there was continued slow uplift and erosion, basin and valley widening, and some faulting and adjustments along existing structures.

Iconic and inspirational landscapes

The spectacular, rugged and evocative Hebridean landscapes we visit and marvel at today are geomorphologically young. Glacial and interglacial cycles during the Quaternary removed much of the landscape described above, and Holocene processes continue to fashion the development of some truly stunning landforms. Despite their ultimate origins during the hot and violent times of the mid-Palaeocene 60 million years ago, they are largely the products borne of Quaternary glacial erosion, mass movement and the post-glacial effects of scarp retreat, sea-level changes and ongoing coastal processes — for example the famous significant landslips of the Storr and Quiraing.

Whether it is the magnificent displays of columnar jointing on the island of Staffa, the impressive rock pinnacle of the Old Man of Storr, or the eerie, unworldly terrain of the Quiraing, the lava field landscapes of Mull, Skye and the Small Isles are justifiably considered some of Scotland's most iconic. Long ago they entered local folklore, engendering formation myths and many legends, and, once discovered by the wider world, have inspired artists, authors, poets and musicians. These landscapes regularly feature as the backdrops to films and television programmes and adverts; and are important assets of Scotland's tourism industry. Geological attributes notwithstanding, they are among the most celebrated of Scottish landscapes (Fig. 50).

Figure 50 Iconic, Evocative and Inspiring Landscapes: painting of Staffa by the American artist Thomas Moran (1837–1926).

Summary and conclusions

In keeping with the theme of 'A Feast of Geodiversity', I hope I have convinced you that the lava fields of the Hebridean Igneous Province are considerably more 'geodiverse' than you might otherwise think. Few geological formations in the UK can be said to offer greater opportunity for the parallel study of such disparate disciplines as igneous petrology, physical volcanology, sedimentology, stratigraphy, palaeontology and palaeolandscape development. They are an excellent case study demonstrating the often-intimate relationships that existed between coeval volcanic, sedimentary, and biotic systems and processes during the construction of a long-extinct volcanic field.

[The talk concluded by showing a short video — a fly-passed of the island of Staffa set to the evocative Mendelsohn's 'Hebrides Overture'.]

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Book Review

Jerram, Dougal, Scarth, Alwyn, and Tanguy, Jean-Claude 2017 *Volcanoes of Europe* (2nd edn). Edinburgh: Dunedin (ISBN 978-1-78046-0420; paperback, 278pp; £29.99)

This book is a treasure trove of information on European volcanoes. The authors may consider this their 'magnum opus'. It is certainly large, being slightly smaller than A4 but weighing in at 900g (2lbs). But its main 'weight' is in the volume and depth of the information it contains. The time spent researching alone must have been huge.

There are nine chapters, starting with an introduction, which I found was good revision of igneous processes. Chapters on volcanoes and their development over time (not all currently 'live') in Italy, Greece, Spain, Portugal, Iceland, Norway (the Arctic islands), France and Germany follow. There is an extensive bibliography, adequate glossary, vocabulary (giving meanings of local language terms such as 'fossa', meaning crater in Italian, and 'rhaun', meaning lava flows in Icelandic), a list of eruptions in Europe in historical times by country (not every country mentioned above has had an eruption since 6000 BCE) and an index.

Each chapter follows a similar pattern, starting with an introduction giving the regional picture. Then individual volcanoes or volcanic regions are covered in detail. And what detail! This is not just the actual geology, but the history of how the eruptions have developed over time and affected the areas. Historical accounts (some by the likes of Pliny the Younger) are quoted in yellow boxes within the text. There are also occasional blue boxes introducing the scientists such as Ben van Wyk de Vries, Professor of Volcanology at Clermont-Ferrand in the Auvergne. The text is interspersed with plenty of full-colour diagrams, although the labelling/matching to the text does contain a few errors/typos in some places (annoying but not too problematic and mainly in Chapter 1). The images are generally excellent and in full colour.

It is a fascinating read and will be of great help when I visit some of these places. I will, however, scan the pages I need and carry them on my Kindle rather than carry the book. All that said, I feel that this is a 'dip in, dip out' reference book, not one to read cover to cover (unless you have oodles of time), but well worth owning if you have an interest in volcanology. At £29.99, it is also good value for money.

— Jane A Michael, OUGS Archivist and Review Officer, BSc (Hons) (Open)

Book review

Wright, T. J., Ayele, A., Ferguson, D. J., Kidane, T., and Vye-Brown, C. (eds) 2016. *Magmatic Rifting and Active Volcanism.* London: Geological Society, Special Publication 420 (ISBN 978-1-86239-729-3; hardback, 384pp; £120.00)

In September 2005, a rapid and intense rifting episode occurred in the Afar region of Ethiopia, producing up to 10m of extension across a 60km long rift segment. This was associated with the injection of *c.* 2.5 km^3 of magma into a dyke separating the Nubian and Arabian plates, with both horizontal and vertical multi-metre-scale displacements along this boundary. An international collaboration was quickly set up to deploy seismometers and GPS equipment; monitored by the Afar Rift Consortium, further dyke intrusions over the next five years yielded more extension, eruptions and seismicity. This book is based around the themes discussed at a subsequent scientific workshop on 'Magmatic Rifting and Volcanism' held in Addis Ababa, following the progress of rifting from the first stages of continental break-up through to full seafloor spreading. There is also a section on some geohazards that may be presented by active magmatic rifts such as those found in Afar. An introductory chapter delves into the background to the genesis of the book, sets out the thematic arrangement, goes into some detail on each of the articles found therein and references numerous other works that have come out of this period of research. As one might expect for a book of this nature, there is a lot going on in these pages; I will simply give one example from each of the themes:

1. The role of magmatism in continental rifting

Why not start with the fundamental question: 'Why is Africa rifting?' This article uses models of lithospheric stress and strength to show that while extensional stresses caused by slab subduction at distant plate margins are significant, and those derived from a shear wave model of mantle flow even more so, they are still about an order of magnitude too low to rupture strong cold, dry, thick continental lithosphere. The authors strongly suggest that in addition to pre-existing lithospheric weaknesses and thinned regions, in order to reduce the strength of the African plate enough to rift, zones of focused melt must be present.

2. Magma-dominated rifting in the Afar triple junction

Here I particularly found the article on magnetotelluric imaging of inactive and active magmatic segments in the Afar region of interest; I had done a week-long electrical resistivity survey of the relatively shallow subsurface gravel and sand fill and limestone bedrock of a half-graben near Corinth as my final year physics project many moons ago but was unaware of its potential to image the plumbing system of volcanoes! Analysis of profiles across segments of the subaerial Red Sea arm of the Afar triple junction show that even inactive magmatic segments still contain large volumes of available magma and partial melt, but that the currently active segments contain an order of magnitude more.

3. Mid-ocean ridges and continental margins

As someone with fond memories of S330 Oceanography, which first introduced me to overlapping spreading centres and their ilk, I was rather taken by the review article on tectonic and magmatic segmentation of mid-ocean ridges and segmentation hierarchies. Much more is now known about ultraslow-spreading ridges such as the Gakkel Ridge in the Arctic Ocean, providing comparison with old favourites such as the fast-speading East Pacific Rise.

4. Hazards from magmatic rifts

Even during these rifting episodes, the construction and filling of a long-planned (1960s!) large dam spanning the Awash Gorge continued in a location not far from a number of significant 20th-century earthquake epicentres and in an actively deforming zone near the triple junction. This would make very interesting reading for anyone contemplating a Geohazards project!

It is pleasing to see that the authors have made the introductory chapter of this book available under Open Access for those wishing to peruse a little further (see http://doi.org/10.1144/SP420.18). Several other articles are also available at no cost to the reader; I do wish that more institutions were open minded about accessible publishing!

— Stuart Swales, OUGS Treasurer, OUGS Webmaster

Rock Slope Failure (RSF): the shaping of the mountains of Britain by huge postglacial rockslides and slope deformations

David Jarman

[Unfortunately, David Jarman was unable to complete a write-up of his lecture as an article for the OUGS Proceedings*. In communications about writing up his lecture, Mr Jarman requested and was provided with a near-verbatim transcription of his lecture recording. However, there were nearly 100 queries in the text of the transcription, and editing of this text into a readable article was not possible. Mr Jarman informed the OUGS that he could not supply replies to queries sent to him, nor supply any illustrations to illustrate his text, by the time of our publication deadline. Therefore, according to our OUGS Symposium lectures policy, it is only possible to publish the abstract he submitted to the OUGS 2017 Edinburgh Symposium Committee for the Symposium brochure.]*

Abstract

Few people realise — as it's not in the textbooks and scarcely touched on in guides, information boards or Geopark displays — that the [Scottish] Highlands are host to a world-class array of rockslides, rock avalanches and rock deformations. There are at least 850 montane rock slope failures (RSFs) on the mainland alone, of which more than 170 exceed 0.25km^2 in extent. They are not easily discerned from roads and glens — until you know what you are looking for — but many have dramatically reshaped ridge crests and summits. After a quick introduction to the engineering geology, we tour the Highlands in pursuit of the finest examples, taking in Ben Lomond and the Arrochar Alps, Lochaber, Affric and Kintail, Torridon and north-west Sutherland. Have these RSFs occurred because the glaciers melted and withdrew support from steepened valley sides, after prolonged rainfall or snow-melt, or in an episode of severe earthquakes as the land rebounded from ice-sheet unloading? Or could there be a more subtle explanation?

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Book review

Torsvik, Trond H., and Cocks, L. Robin M. 2017 *Earth History and Palaeogeography*. Cambridge University Press (ISBN 987-1-107-10532-4; 317pp; hardback £49.99)

This reference book provides a beautifully illustrated history of our planet, Earth, over the past half billion years. Much of the tome provides detailed worldwide palaeogeographic maps and tectonic history, in chronological order from the Cambrian period, but it also contains a wealth of background and reference material.

After the introduction, the first chapters cover the science behind the location of former continents and terranes. Many independent methods have been assimilated with well described explanations of changes in ancient magnetic polarity, hot spot reference frame reconstructions, apparent polar wander paths, calibration of longitude and how the relative positions of the lithospheric plates are calibrated upon the most stable, (geographically and tectonically) cratonic areas of Africa. These are then assimilated with the more familiar concepts from the fossil and rock record, assessing climate and sediment distributions.

A further chapter explains how the Earth is divided into several hundred tectonic units of various sizes and describes them regionally. England is part of the Eastern Avalonia unit, and independent of Scotland and most of Europe. Thereby hangs a tale!

Pre-Cambrian history is briefly discussed, but the majority of the text comprises detailed palaeogeographic history and reconstructions, which appear to be well indexed. Individual chapters cover the time periods from the Cambrian to the Neogene and Quaternary. There are lovely pictures of fossils too. Each chapter looks not solely at the reconstruction maps but also on aspects of Earth's history such as tectonics, flora and fauna, and focuses upon key events of the time, such as the Origin of Birds, in the Jurassic chapter. The book points out that the accuracy of palaeogeographic reconstruction improves considerably towards the present.

The final chapter discusses climate change and the factors affecting it over the Phanerozoic.

The authors have generated software to make flat maps from a spherical Earth. They have made available supplementary online material, which permits anyone to make their own reconstructions at any time period since 540 million years ago.

A small point to note, is that a few of the very detailed figures have long explanatory 'titles', which run over two pages and the book would certainly read more easily if these were printed closer to the map or diagram.

Overall, it is a wonderful reference companion to put any geological read into context.

— Dr Maggie Deytrikh, BSc Hons (Geosciences)

Book review

Becker, R. T., Königshof, P., and Brett, C. E. (eds) 2016 *Devonian Climate, Sea Level and Evolutionary Events*. London: The Geological Society, Special Publication 423 (ISBN 978-1-86239-734-7; 481pp; £130)

The Devonian Period was an exciting time of global events, when conditions such as warming, anoxia, sea level changes and volcanism triggered evolutionary trends! For example, there was a 'predator revolution'; and also a 'nekton revolution', which, although it initially sounds less exciting, in fact gave rise to ammonoids and fish, and to the oldest tetrapods. Add this to the growth of reef complexes and the 'greening of the land' by plants and you begin to have an idea of why this was such a noteworthy Period!

In common with other Special Publications (SP) from the Geological Society this is a set of papers around a theme, which, in this case, grew from collaboration between the International Geoscience Programme (IGCP) and the International Union of Geological Sciences (IUGS). A conference on Devonian ecosystem and climate evolution was followed by one on climate change and biodiversity patterns in the Mid-Palaeozoic and much of what is in this SP came out of those events. The 14 papers are introduced by the editors (the Introduction is Open Access and available at http://sp.lyellcollection.org/content/423/1/1.full) and are wide-ranging, covering topics from sea level fluctuation to palynology, brachiopod faunas, conodonts, carbon isotopes, coral crises, extinctions, global Annulata events, stratigraphy and the Devonian–Mississippian shift from greenhouse to icehouse. Each individual paper is fully referenced and the book has a comprehensive index; there are plenty of figures, in colour where appropriate.

Just to give a flavour of the book as a whole, the final paper, 'Greenhouse to icehouse: a biostratigraphic review of latest Devonian–Mississippian glaciations and their global effects', looks at the greenhouse-to-icehouse transition at the start of the Late Palaeozoic Ice Age (LPIA), via three short glaciation events. The authors use primary evidence from South American high latitude diamictite deposits and striated pavements (sound familiar to any S369 students?), which they link to more widespread, lower-latitude records. They highlight the uncertainty surrounding the LPIA, and conclude by identifying a need for high-resolution stratigraphic studies.

The book is at a level most suitable for final year (Level 3) undergraduates, or post graduate/MSc students. I know that I found my recent experience of S369 very helpful — many topics in this book 'rang bells'!

— Linda Fowler, BA Hons (Open), MSc (Earth sciences) student

Geodiversity in Fife

Richard A. Batchelor (Chair, geoHeritage Fife)

Rosalind Garton (Secretary, geoHeritage Fife)

Public interest in Geology has never been greater. Today the media takes full advantage of new developments in science, using modern technology and animations to convey geological observations and theories to audiences of all ages. 'geoHeritage Fife' was set up to focus on the local rocks of Fife as a way of getting people involved with the rocks on their doorsteps.

At the beginning of the 20th century the Director of the Geological Survey, Sir Archibald Geikie, commented that:

> *If I were asked to select a region in the British Isles where geology could best be practically taught by constant appeals to evidence in the field, I would with little hesitation recommend the East of Fife as peculiarly adapted for such a purpose.*

His support resulted in the foundation of a degree in Geology at the University of St Andrews and, ever since, the unrivalled local outcrops have been used to train undergraduates.

In 2000, local geologists Richard Batchelor and Rosalind Garton, together with adult education students from the University of St Andrews Open Association, decided it was time to make the interpretation of the outstanding local geology more accessible, both for Fife residents and visitors. With a rich diversity of rocks, from fossils and folds to lavas and volcanic necks, and a coastline of nearly 200km, Fife is well placed to demonstrate the variety of geological features in eastern Scotland (Fig. 1).

To this end, geoHeritage Fife was set up as a registered charity (SC032509) and a fully constituted society. It publicises Fife's geological heritage, provides educational resources in geology, and promotes geotourism in Fife. It currently has 38 members, who participate in field excursions, suggest new itineraries, and 'test-walk' new geological trail leaflets. Its Chair, Richard Batchelor, is Honorary Research Fellow in the School of Earth and Environmental Sciences at the University of St Andrews. Its Secretary, Rosalind Garton, has been Geology Tutor to the Open Association for more than 30 years, and uses the unrivalled sections in Fife for teaching her popular classes. As the local Local Geodiversity Sites organisation (formerly RIGS), geoHeritage Fife also has a duty to inform the local planning authority about new geologically important sites. Contentious planning applications are referred to the group for assessment and comment (Figs 2, 3, 4 and 5, *all overleaf*)

To date, geoHeritage Fife has produced ten leaflets explaining aspects of geology for St Andrews, St Monans, Kingsbarns, Kinghorn and Kirkcaldy, Aberdour, Dura Den, Wormit, Norman's Law, Holy Trinity Church in St Andrews, and Historical geoscientists at St Andrews. It has built a geological wall in St Andrews (consisting of rocks representative of Fife's geology) and a stone cairn in Ladybank (incorporating examples of glacially derived stones), created a Jurassic Garden in St Andrews, and erected plaques in St Andrews to two famous geologists — mineralogist Matthew Heddle and palaeontologist Charles Lapworth.

The foreshore near St Andrews has examples of folded rocks, plant and shell fossils, remains of a volcano and the fossilised tracks of a giant water scorpion. St Monans has a similar assemblage of geological structures. The area around Kinghorn and Kirkcaldy shows good examples of igneous rocks, which flowed over and intruded sedimentary rocks. There are also rich assemblages of fossils, and both thrust and normal faulting (with breccias) can be inspected. The shore at Wormit in North Fife shows good examples of Devonian volcanic activity, with lava flows, volcanic conglomerates, inter-lava sediments

Location map of geoHeritage Fife sites:

1 St Andrews Geological Trail
2 Geological Wall in St Andrews
3 Historical Geoscientists at St Andrews
4 Jurassic Garden
5 Holy Trinity Church, St Andrews
6 Kingsbarns Geological Trail
7 St Monans Geological Trail
8 Kinghorn — Kirkcaldy Geological Trail
9 Aberdour Geological Trail
10 Geology of Ladybank — record in stone
11 Dura Den Geological Trail
12 Norman's Law —a geological perspective of views from the summit
13 Wormit shore Geological Trail
14 Lomond Hills

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Figure 2 Rock and Spindle, the remnants of a Carboniferous volcano near St Andrews.

Figure 4 Saddleback (plunging) anticline, St Andrews.

Figure 3 View to St Andrews from the Maiden Rock.

Figure 5 Geological Wall, St Andrews.

Figure 6 Thrusts near Kinghor.

Figure 7 Volcanic conglomerate (Devonian), Wormit.

(some with evidence of fossil algal mats), a late-stage micro-granite intrusion and a substantial glacial erratic of Dalradian schist — geoHeritage Fife also organises excursions to explore this wonderful local geodiversity (Figs 6 and 7, *previous page*; Figs 8, 9, 10 and 11, *this page*).

Figure 8 Felsite intrusion (Devonian), Wormit.

Figure 9 Arthropleura tracks, Boarhills.

In 2009, a new departure for geoHeritage Fife was the winning of grants worth £7,700 to commission a plaster cast of the fossil trackway of a giant arthropod that was considered at risk from erosion and vandalism. Part of the cast is now on display in the Museum of the University of St Andrews (Figs 12 and 13).

Figure 10 Dolerite sill, Kirkcaldy.

Figure 11 Fossil crinoids in limestone, Kirkcaldy.

*Figure 12 Trackway of giant water scorpion '*Hibbertopterus*', and right, Figure 13 Plaster cast of part of the trackway, MUSA, St Andrews.*

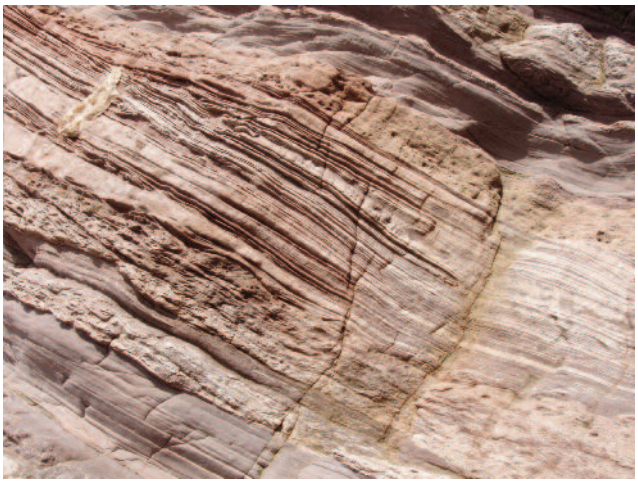

Figure 14 Textures in sandstone, Kirkcaldy.

Then in 2010, it organised a photographic competition to encourage the public to observe, artistically through the camera lens, Fife's geological heritage. The competition was judged by professional photographers and elicited an amazing 150 entries! (Figs 14 and 15)

Two years later geoHeritage Fife joined the 'Living Lomonds Landscape Partnership' (LLLP), a consortium of local groups and charities in Fife, and the consortium put in a bid to the Heritage Lottery Fund for a three-year multidisciplinary project to explore the natural, cultural and built environment of the Lomond Hills west Fife. The bid was successful, and £1.7M was awarded to the consortium, led by Fife Coast and Countryside Trust. geoHeritage Fife's share of this grant was £11.5k and we also raised match funding (see Acknowledgements). These funds were used to do fieldwork for and in the writing of four geological trail leaflets describing the features of the East Lomond, West Lomond and Bishop Hills, and the Building Stones of Falkland, a historical and picturesque village (Figs 16, *below*; 17 and 18, *opposite*).

The group continues to thrive and new ideas and requests flow in both from its members and from the public. A leaflet on the *Building Stones of St Andrews* is currently in draft , and trail leaflets for other geological sections in Fife are planned.

Given our success and the enthusiasm of our members geoHeritage Fife encourages others to explore their home areas and be prepared to extol the virtues of the local geology to make it accessible to the public, giving advice on successful approaches and, particularly, on potential sources of funding for projects such as these.

Figure 15 Basalt columns, Leslie (Photograph: Gilroy).

Acknowledgements

Over the years geoHeritage Fife has been financially supported by Fife Council, Scottish Natural Heritage, the Curry Fund of the Geologists' Association, The Royal Society, Scottish Enterprise Fife, The Skene Group, Kinburn (St Andrews) Charitable Trust, Edinburgh Geological Society, and St Andrews Community Trust, as well as by members' subscriptions and donations. The Heritage Lottery Fund contributed the £11.5k matching fund described above.

Figure 16 View of Bishop Hill (left) and the twin peaks of the East (centre) and West (right) Lomond hill. Both peaks are formed by dolerite intrusions. The ledge to the right of the West Lomond is formed by an outcrop of the Midland Valley Sill.

Figure 17 Limestone quarry, Bishop Hill.

Figure 18 Stone wall in Falkland, with a mixture of igneous and sedimentary stones.

Book review

Klein, Cornelis, and Philpotts, Anthony 2016 *Earth Materials: Introduction to Mineralogy and Petrology* (2nd edn). Cambridge University Press (ISBN 978-1-31660-885-2; 616pp; hardback £100, paperback £49.99)

When I finished my Open University earth science courses many years ago I wish this book had been available at the time. The content in many ways fills in many of the gaps in my knowledge and expands upon what I learned about mineralogy and petrology with the OU. That the book is in its second edition indicates its usefulness and popularity and has enabled the authors to correct any errors in the first edition.

The book has been produced to the highest standards. Illustrations appear throughout (1,076 of them, all in full colour) and, most importantly, they all support the text. Diagrams are exceptionally well drawn and there are numerous high-quality photographs of rock thin sections and minerals to illustrate specific features detailed in the text.

The book is written in American English (color, aluminum) and designed for the global market, using examples from around the world (including the UK). This has undoubtedly made feasible a far greater print run and the extremely high production values. There are helpful exercises at the end of each chapter to test your knowledge as you progress through the book — 360 exercises in total.

While crystal structures are illustrated in the book it is often difficult to visualise a 3-D structure on a 2-D page. To overcome this restriction interactive software (CrystalViewer) is available on-line from the publisher, which enables you to do all sorts of clever things (including 3-D rotations) with all the common rock-forming minerals. You could play with this software for hours!

The book's content takes the reader through basic mineralogy, crystallography, the formation of the different rock types, economic resources and a brief word on hazard geology. Difficult concepts are often supported by text bsoxes and important new terms are highlighted on first appearance. Several chapters cover material that will be new to OU students and although concepts are carefully explained this is not a book I would recommend to first year students. For example, I found the sections on crystallography and phase diagrams particularly stretching, but rewarding. I would, however, highly recommend this book to students who have exhausted the OU geology courses and want to know more about geomaterials.

Amazon has a 'Look Inside' feature available. While you cannot see the many stunning illustrations and diagrams you can still get a comprehensive overview of the book's content to help decide if this is the book for you. The price may be off-putting for some, but still compares favourably with other learning materials. When writing this review, and with little effort, I found new copies available on-line at half price. You may do better.

— Geoff Downer, BSc Hons (Open)

Book review

McManus, John 2017 *Coal Mining in the East Neuk of Fife*. 2017. Edinburgh: Dunedin (ISBN 978-1-7804-6072-7; 188pp; hardback £24.99)

As someone who grew up in the countryside of West Fife, among the signs of coal mining, bings, subsidence, old miners out walking to get country air, I didn't realise that there had been very much coal mining activity in the east of the Kingdom. It was all fishing and farming, wasn't it? — the Fringe of gold on the Beggar's Mantle, as the old saying goes. It was fascinating to discover that several separate coalfields were worked in the East Neuk and Prof. McManus has set out to catalogue these in this book. There is a largely irrelevant section on the geological setting at the beginning, more about general plate tectonics than the Carboniferous of Fife, although this other information is to be found later in the book.

The following sections on the history of coal working and methods employed are useful guides to anyone new to the subject of coal mining. Once the author gets going on the coalfields, the coals worked and the mines, however, this is where the fruits of his research are to be seen, with the seams, individual workings and amounts of coal raised all covered in detail; as most of the pits had closed by the early 1900s, this has involved a considerable amount of delving in old documents. There are also maps and sections of the surface and underground workings, showing that it isn't just at the immediate shaft surroundings that the workings can affect the surface.

In short, this is the book that tells you all you wanted to know about a part of the economic history of what is now an agricultural district, but which had a very different past for a few hundred years.

— Don Cameron, BGS, OUGS Secretary

Spireslack surface coal mine — a national asset for geology and learning in the Midland Valley of Scotland

A. G. Leslie, R. Ellen and M. A. E. Browne

all BGS Scotland
The Lyell Centre
Research Avenue South
Edinburgh EH14 4AP, UK
corresponding author: agle@bgs.ac.uk

Abstract

The recent economic collapse of the opencast coal mining industry in the Midland Valley of Scotland has left behind a number of abandoned voids that reveal large-scale 3D exposures in strategically important strata. One of those is the former Spireslack Surface Coal Mine near the former mining village of Glenbuck in East Ayrshire. A strong case can be made for retaining such large-scale geological sections that might otherwise have been lost to science. While some might see the opencast workings at Spireslack as industrial scars on the Scottish landscape, they can instead become national assets for multidisciplinary Geoscience research and learning in general. Such opencast sites can also provide a rich visitor and/or learning experience for the wider public, showing coal geology and the working life of previous generations.

Figure 1 Overview of the Spireslack Surface Coal Mine in East Ayrshire, looking west. The high wall on the left of the view is up to 130m high; the buff-coloured smooth engineered pavement on the right marks the position of the Namurian Top Hosie Limestone (Lower Limestone Formation), dipping here at 35°–40° to the SSE (BGS Photo: P917869).

Introduction

Spireslack is an abandoned surface coal mine (SCM) at Glenbuck in East Ayrshire in the Midland Valley of Scotland, currently owned by the Scottish Mines Restoration Trust (SMRT) (Fig. 1). The Glenbuck area has a long history of mining, beginning with shallow bell pits sunk for ironstone in the late 18th century. Underground coal extraction was active in the late 19th to early 20th century, followed by later 20th to 21st century surface coal mine operations. All of these operations were focussed on extensive and thick coal seams within the Carboniferous Limestone Coal Formation, one of the main coal-producing units in the Midland Valley of Scotland. Underground coal mining within the Spireslack area was accessed through the Grasshill Pit, which closed in 1931 and presaged the final decline of Glenbuck village — of which there is little trace today. Surface coal mining at Spireslack began around 2000, ending in 2008 with the decline of the Scottish coal industry and leaving its mark on the present-day surface. Spireslack SCM, and the neighbouring Grasshill and Ponesk mines are indicated as 'SGP' on Figure 2a *(overleaf)*.

As a result of surface coal mining practice, the so-called 'Main void' at Spireslack SCM has created a spectacular worked face 1km long and up to 130m high (Fig. 3, *overleaf*); this void exposes almost the entirety of the Limestone Coal Formation. In addition, worked faces elsewhere across the site expose sequences from the Lawmuir, Lower Limestone and Upper Limestone formations (Fig. 2b). The geological structures and strata exposed here are not typically seen on anything approaching the same scale or completeness/continuity within natural sections across Scotland, or farther afield in the UK, and so deliver a valuable resource for geoconservation in that regard if in no other.

In addition, however, Spireslack also preserves evidence of the earlier generation of mining, where 20th–21st century surface mine operations are superimposed on underground workings from the 19th to 20th century (Figs 4 and 5, *page 91*). Perhaps Spireslack's greatest asset is the opportunity that it provides for the visitor, expert and non-expert alike, to stand inside a three-dimensional, architectural arrangement of geology, and so begin to appreciate how the geological features all relate to one another. Though Spireslack now constitutes a very large hole in the ground that some might regard as a blight on the landscape, this article will set out some of the reasons why Spireslack can instead be regarded as a great opportunity to learn about geology, and of the industrial activities that relied upon that geology.

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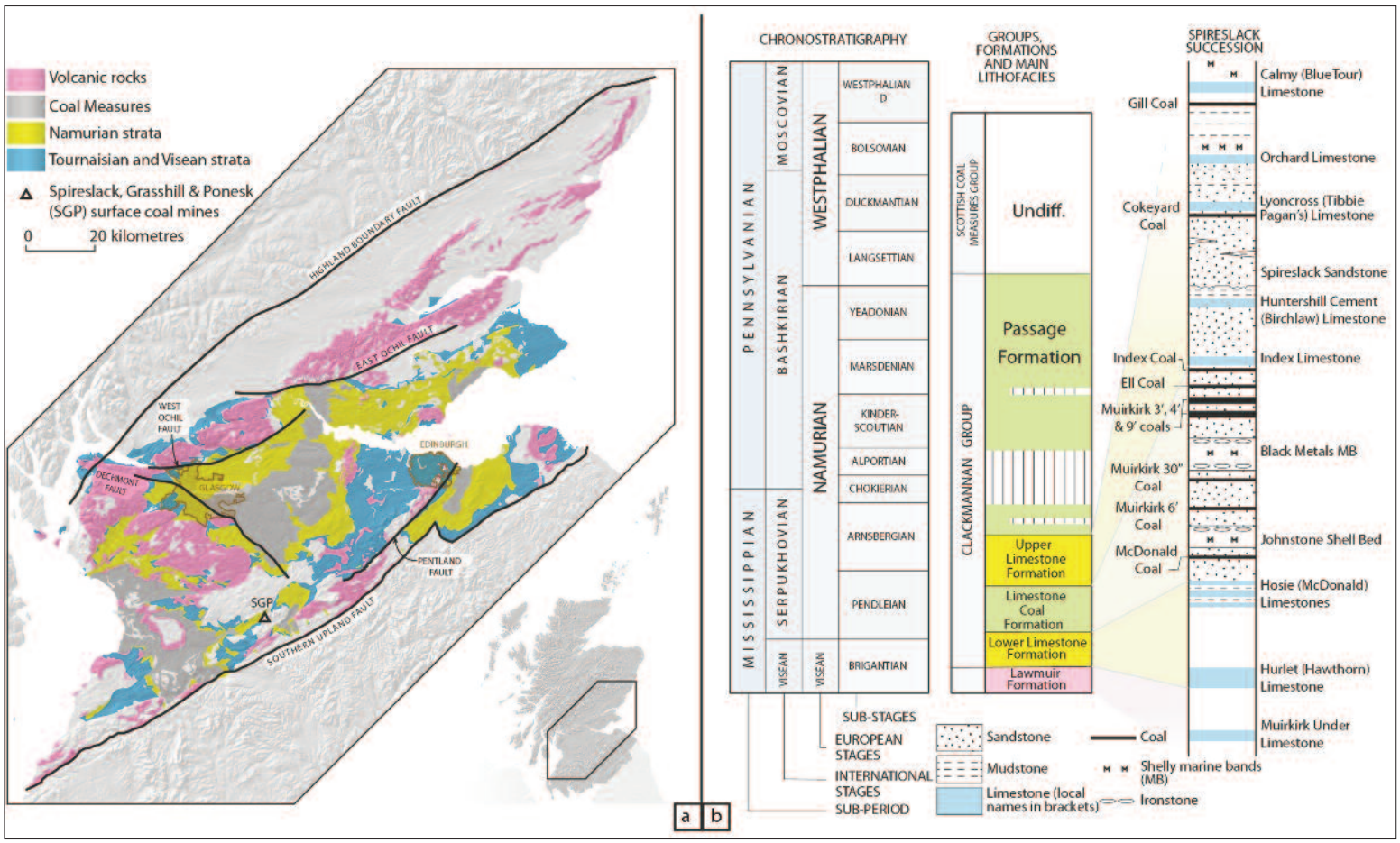


Figure 2 (a) Generalised Carboniferous geology of the Midland Valley of Scotland, with location of the Spireslack, Grasshill and Ponesk surface coal mines (SGP). Base image derived from NEXTMap Britain elevation data from Intermap Technologies; (b) Stratigraphical framework for coal-bearing strata across SGP, based largely on data collected from the Spireslack surface coal mine (where the strata are exposed most continuously) in the Midland Valley of Scotland.

At the time of operations, the scale and heavily mechanised nature of the activities on such surface mine sites meant that opportunities for research were restricted; visits were thus often restricted to a view gained from a safe distance. These sites were, to some degree, missed opportunities to examine stratigraphic and structural geological details, or to gain an understanding of the nature of the sub-surface and how it might respond to anthropogenic activity. The rocks exposed at Spireslack, Grasshill and Ponesk have now been audited and described by the British Geological Survey (BGS) (Ellen and Callaghan 2015; Ellen and Callaghan, 2016; Ellen *et al.* 2016), and are currently under evaluation and review for designation as GCR sites by the BGS. The GCR proposal describes the Spireslack Conservation and Glenbuck Conservation sections, located respectively in the main void at Spireslack and in an area near by that lay just to the north-east of the now disappeared village of Glenbuck. Geoconservation of the Spireslack, Grasshill and Ponesk sites will be a positive outcome for these abandoned surface coal mines and enable teaching and research to be carried out for many years to come. A Scottish Carboniferous Research Park (SCARP) has been proposed (Leslie and Browne 2016).

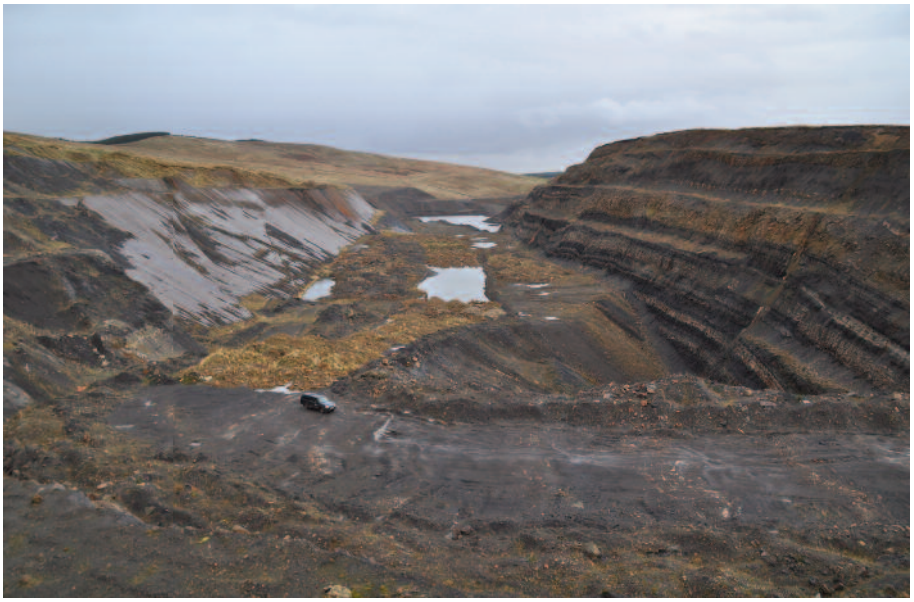


Figure 3 Overview of the 'Main Void' at the Spireslack SCM, looking east-northeast. The inclined engineered pavement on the left of the view was formed in the top Hosie (McDonald) Limestone for safe workings; the high wall on the right is some 80m high in the centre of the view. The void and high wall together expose an almost complete succession in the Namurian Limestone Coal Formation and a major part of the Upper Limestone Formation. The site is currently owned by the Scottish Mines Restoration Trust (SMRT).

Figure 4 Wooden pitprop emerging from the mined-out position of the Muirkirk Nine Foot coal in the high wall section at Spireslack SCM. The wooden prop dates from the early 20th century underground mining (BGS Photo: P917881).

Geological setting

Rocks of Carboniferous age occupy much of the Midland Valley of Scotland, formed originally as an ENE–WSW trending graben bounded to the north-west by the Highland Boundary Fault system and to the south-east by the Southern Upland Fault system (*see* Fig. 2a). These bounding faults were active in the Carboniferous as reactivated structures, originally Caledonian, now involved in the control of sedimentation. These faults behaved initially as sinistral strike/oblique-slip faults and were then subsequently re-activated (post-Westphalian?) during dextral strike/oblique-slip deformation (Browne and Monro 1989; Underhill *et al.* 2008). The numerous Carboniferous basins formed within the Midland Valley of Scotland graben were separated from those to the south in the Solway and Northumberland regions by the Lower Palaeozoic rocks of the Southern Uplands block, that formed a positive, mainly emergent, structural high throughout the Carboniferous Period. The Scottish Highlands Precambrian and Lower Palaeozoic rocks to the north of the Highland Boundary Fault were similarly a positive and mainly emergent area at this time.

Spireslack SCM is located within the Muirkirk Syncline, a broad upright NE–SW trending fold such that strata in the SCM 'main void' dip at 30° to 40° SE on the north-western limb of this fold (*see* Figs 1 and 3). Folding was accompanied by faulting in a ductile-brittle stress regime; consequently, the folded strata are dissected by multiple NNE–SSW and NW–SE striking curviplanar, typically left-lateral (sinistral), oblique-slip faults. The faults form a major part of an array that is geometrically and kinematically consistent with an overall pattern of sinistral transpression affecting these rocks at this time in the Carboniferous (Leslie *et al.* 2016).

Marine influence reached its peak during the deposition of the mixed shelf carbonate and deltaic succession of the Namurian Clackmannan Group (Browne *et al.* 1999; *see* Fig. 2b). Syn-sedimentary tectonic movements were prevalent from the late Viséan and especially during Namurian times. In Ayrshire, Namurian rocks are associated with ENE–WSW striking faults controlling marked changes in depositional thickness (Read *et al.* 2002).

The sections making up the succession exposed at Spireslack are latest Viséan to Namurian in age (*c.* 330Ma to 325Ma). Marine limestone and mudstone units, and shallow deltaic to fluvial sandstone and mudstone units are all present, interbedded with coal layers and related palaeosol units (seatearths). The Spireslack succession begins with the Lawmuir Formation of the Strathclyde Group, passing upwards into the Lower Limestone, Limestone Coal and Upper Limestone formations of the Clackmannan Group (Browne *et al.* 1999, Patterson *et al.* 1998; *see* Fig. 2b). These marine and fluvio-deltaic strata were deposited as upward-coarsening cyclic packages, partly recording a reduction in water depth, while the locally upward-fining strata and coals were formed on floodplains, and in swamps and peat bogs.

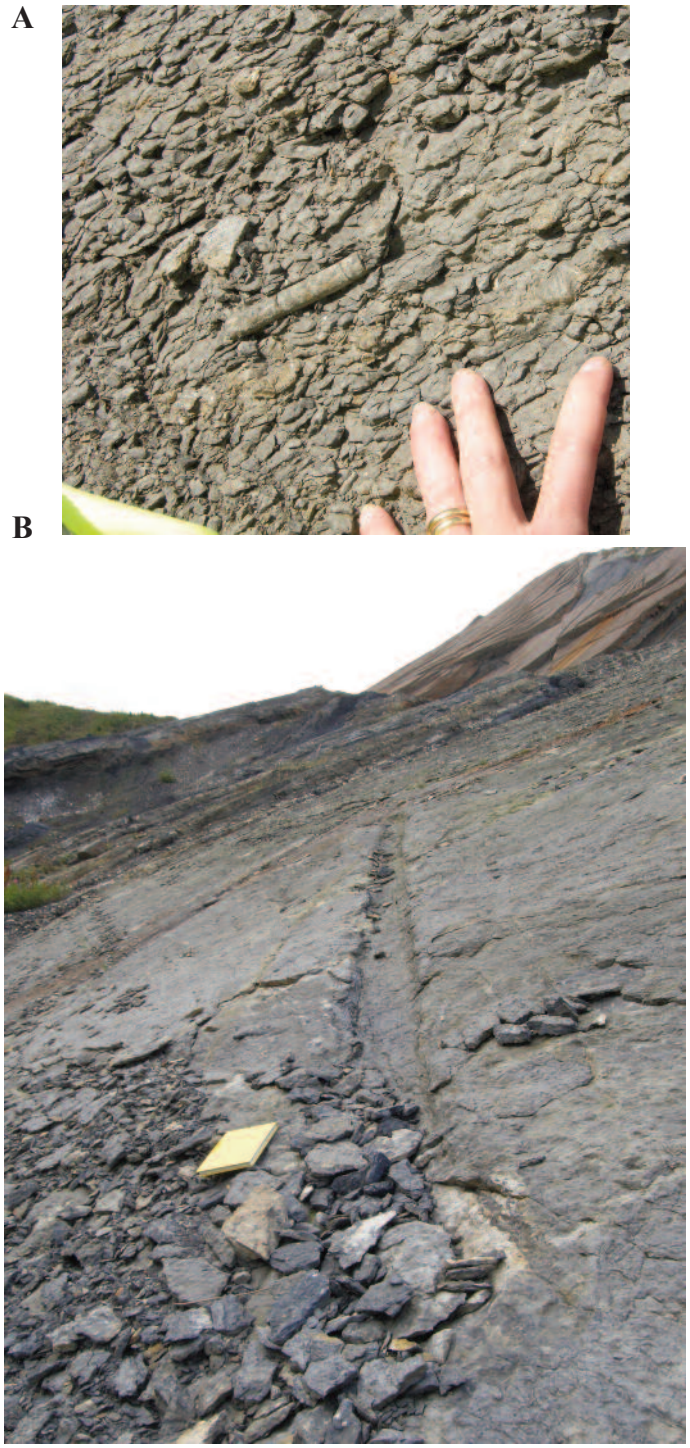
Figure 5 Opencast operation in the eastern part of the Spireslack surface coal mine, September 2004. The grey and brown-stained (oxidised) pavement in the top left is the Top Hosie Limestone. Parallel, greyish-white scratches made by the diggers mark the excavation levels on the Muirkirk Six Foot pavement (seatearth) in the centre left of the view (BGS Photo: P579544).

Following on from the Carboniferous, the Spireslack SCM shows only evidence of minor baryte mineralisation that may mark the southernmost limits of the Muirshiel-Gasswater-Nutberry Hill zone of NW-trending vein mineralisation of possible early Permian age (Cameron and Stephenson 1985). In the Palaeogene, a number of microgabbro (dolerite) dykes were emplaced into the Carboniferous strata at Spireslack, mainly along a NW–SE trend. Both the baryte mineralisation and the much later dyke emplacement have exploited reactivation and opening of the earlier-formed faults on that trend. The dykes are typically penetratively decomposed.

Carboniferous stratigraphy at Spireslack and adjacent sites

The Carboniferous stratigraphical succession exposed at Spireslack, and in the adjacent sites at Grasshill and Ponesk, extends from the Brigantian up into the upper part of the Arnsbergian (*see* Fig. 2b). The characteristics of the constituent formations are described briefly under the following subheadings, based on new data collected from the Spireslack SCM.

Figure 6 Carboniferous geodiversity in the Spireslack strata: (A) fossiliferous mudstone of the Lawmuir Formation with abundant crinoid fragments, and columnals up to 100mm long (BGS: Photo P8252026); (B) Lepidodendron *cast 3m long, preserved* in situ *within the McDonald Coal seatearth (BGS Photo: P8252140); (C) fossilised hybodont shark spine preserved on the Top Hosie (McDonald) Limestone pavement in the north-west wall of Spireslack (BGS Photo: P8252089); (D)* Trilobite pygidium *(*Paladin *sp.) preserved on the Top Hosie (McDonald) Limestone pavement; (E)* Rhizocorallium *trace fossils on the surface of the Top Hosie (McDonald) Limestone pavement (the septae are 5mm across).*



Lawmuir Formation (Brigantian)

The Lawmuir Formation comprises a variable succession of sandstone, siltstone, mudstone and ironstone, and includes the *c.* 600mm thick Muirkirk Under Limestone containing both Gigantoproductus and compound coral bands. The mudstone is often richly fossiliferous with abundant crinoid debris (Fig 6A, *previous page*). A thin coal seam lies below this marine unit. Purple-grey mudstone, siltstone and sandstone otherwise dominate, often weathered and strongly fractured, the latter in response to faulting. The upper section of the formation comprises 10m of dark-grey fossiliferous mudstone with red-brown ironstone ribs.

Lower Limestone Formation (Brigantian – Pendleian)

The Lower Limestone Formation consists predominantly of marine mudstone and fluvio-deltaic mudstone and siltstone interbedded with laterally extensive marine shelf limestone. The base of the formation is taken at the bottom of the Hurlet Limestone (locally known as the Hawthorn Limestone); this limestone is characterised by a pale brown and nodular rubbly kaolinitic top containing large productid brachiopods (*Gigantoproductus*) and coral colonies. The top of the formation is taken at the top of the Hosie Limestone (named locally as the McDonald Limestone); this upper unit as a whole comprises a succession of five separate limestone layers, each between 0.5m to 0.7m thick and interbedded with siltstones and mudstones up to 1.2m thick. It is the uppermost limestone layer of this unit ('Top Hosie') that forms the robust engineered north-west wall of the main void (*see* Fig. 3). This large exposure of a single limestone bedding plane displays abundant trace fossils; dark grey branching structures up to 100mm long (?*Planolites*, and *Rhizocorallium*), along with millimetre-sized dark grey narrow traces (?*Chondrites*). In addition, trilobite (*Paladin* sp.), brachiopod and hybodont shark spine remains have been identified at this level (Fig. 6C, 6D and 6E).

Limestone Coal Formation (Pendleian)

The Limestone Coal Formation comprises a fluvio-deltaic succession of upward-coarsening and then upward-fining cycles consisting of mudstone, siltstone, sandstone, seatearth, sideritic ironstone and coal. The formation is *c.* 95m thick as exposed in the semi-continuous section in the 'high wall section' of the main void at Spireslack (Fig. 7). The base of the formation is taken at the top of the Top Hosie Limestone (McDonald Limestones), while its top is taken at the base of the Index Limestone; the latter is also exposed in and along most of the high wall section (Fig. 7).

Evidence of two regionally significant marine incursions is preserved in this formation in the Johnstone Shell Bed and the Black Metals Marine Band. The Black Metals Marine Band is not currently safely accessible on the Spireslack site, but is easily recognised in the high wall section of the main void by its association with three distinctive layers of variably continuous ironstone. The stratigraphically lower Johnstone Shell Bed (a dark-grey mudstone) contains a marine fauna, which in the Muirkirk area is known to consist of *Pleuropugnoides* sp., *Productus concinnus*, *Schizophoria* cf. *resupinata* and *Pernopecten sowerbii* (Patterson *et al.* 1998). Identification of the marine fauna exposed at Spireslack is yet to be undertaken in detail, but includes *Lingula* sp.

Figure 7 The high wall section at Spireslack showing the position of the Index Limestone making the base of the Upper Limestone Formation. The majority of the worked coal seams lay within the underlying Limestone Coal Formation. The Palaeocene dyke intruded into the Carboniferous rocks is one of a number exposed on the site, almost all are now deeply weathered (BGS Photo: P917870).

At least six significant units of sandstone are exposed in the high wall section of the main void at Spireslack (*see* Fig. 7). Each unit of sandstone is observed to be laterally continuous across the high wall section (i.e. from south-west to north-east), and between 2m and 10m thick. Each maintains its general thickness across the exposure, in sharp contrast to the sandstone units in the succeeding Upper Limestone Formation. In the Limestone Coal Formation, the sandstone units display planar cross-bedding and current ripples, and contain organic fragments and ironstone nodules in layers. These sandstones record episodes where water depth gradually fell, forming fluvio-deltaic complexes. Swamps and peat mires, formed above marshy waterlogged palaeosols (seatearth layers), were associated with the prograding fluvio-deltaic complexes. Seatearth layers within Spireslack contain abundant fragments of organic material, consisting commonly of *Stigmaria* roots or *Lepidodendron* trunks (*see* Fig. 6B).

Several of the formerly most economically important Muirkirk sub-basin coal seams are exposed within the main void and high wall sections, each typically overlying seatearth layers. In upwards stratigraphical order these are the: McDonald, Muirkirk Six Foot, Muirkirk Thirty Inch, Muirkirk Nine Foot, Muirkirk Four Foot, Muirkirk Three Foot, Muirkirk Ell and Index coal seams (*see* Fig. 2b). These coals formed in equatorial floral provinces dominated by heterosporous lycopod tree-like rainforests and thick raised peat mires (Phillips and Peppers 1984; Clymo 1987). Figure 8 shows the reconstructed positions of these coal seams within the excavated void space, using the positional data for individual seams captured during the mining operations. It is worth noting here that in an industry where good working waste-to-coal ratios would have been in the order of 15:1 or 18:1, ratios at Spireslack were much greater and more often in the region of 60 to 80:1 and so much more challenging financially.

Upper Limestone Formation (Pendleian to Arnsbergian)

The Upper Limestone Formation comprises cycles of sandstone, with mudstone, siltstone and marine limestone layers, including the regionally significant Index Limestone, the base of which marks the base of the formation. At Spireslack, the Index Limestone is a 1.3m thick grey, hard, compact bioclastic limestone. This limestone contains abundant *Gigantoproductus* cf. *irregularis*, *Latiproductus* cf. *latissimus*, *Pleuropugnoides* sp., *Schellwienella* sp., *Myalina* sp. and *Polidevcia attenuata* (Patterson *et al.* 1998), and represents a maximum flooding episode (Read *et al.* 2002). A conspicuous buff to reddish-brown coloured seatearth and a thin (often less than 200mm thick) impersistent layer of the Index Coal occurs immediately beneath this limestone. The Index Limestone is overlain by a 7–10m thick, black, silty marine mudstone (locally including the silty Huntershill Cement Limestone), itself overlain by an erosive-based multi-storey coarse-grained fluvial to possibly estuarine sandstone (Fig. 8). This fluvial sandstone unit is assigned to the 'Spireslack Sandstone' (Ellen *et al.* 2018, in review).

The Spireslack Sandstone is a composite sandstone unit. The basal part varies from 3–18m in thickness and comprises two distinct channelled sandstone bodies that overlie the mudstone below, across an erosive and locally down-cutting surface (*see* Fig. 8). The lower channel unit is almost entirely composed of lenticular units of structureless or trough-crossbedded sandstone; this lower unit is cut into by an upper channel set comprising asymptotically cross-bedded sandstone with more variable and heterolithic

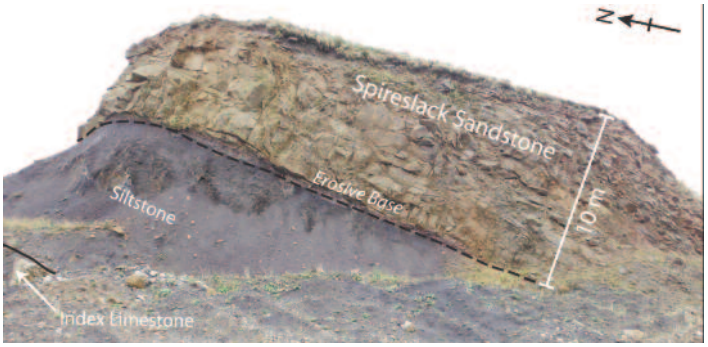


Figure 8 Exposure of the Spireslack Sandstone at the south-west end of the high wall section in the Spireslack SCM site.

channel forms. Both channelled units are overlain by a laterally extensive, 14m thick, asymptotically cross-bedded sandstone with heterolithic toesets heavily bioturbated by *Teichichnus* septate burrows. A 15m thick succession of sandstones and siltstones in conformable planar interbeds overlies this unit, and forms the uppermost component of the Spireslack Sandstone.

A mudstone-dominated siliciclastic marine succession overlies the Spireslack Sandstone and is, in turn, overlain by the 1m thick crinoidal Lyoncross Limestone. This limestone provides correlation with successions elsewhere across SGP and is overlain by a mudstone followed by a further erosive and locally down-cutting fluvial sand body.

The Orchard Limestone is exposed in the excavations at the base of the high wall below outcrops of the Calmy Limestone, but is not currently accessible because of flooding (*see* Fig. 1). This displacement of the younger parts of the stratigraphy from the top to the bottom of the high wall section occurs across a strike/oblique-slip fault that coincides with the south-western limit of the flooded area (*see* following section and Fig. 9). The highest limestone in the formation seen at Spireslack is the Calmy Limestone; it is exposed at top of the north-eastern end of the high wall and comprises a succession of at least four massive, thick limestone beds alternating with siltstone and mudstone layers in a package at least 10m thick overall. The Gill Coal Seam sits beneath the lowermost exposed limestone in this succession. This coal seam is up to 1m thick and contains significant development of pyrite mineralisation. No strata above this level in the Upper Limestone Formation are exposed at Spireslack.

Faulting

The effects of superimposed faulting are clear at Spireslack. The reconstruction in Figure 9 *(opposite)* shows the change that occurs across the fault marking the sub-division of the Spireslack SCM into a strongly folded north-eastern compartment and a more tabular, structurally less complex south-western one. It is this fault that is responsible for the marked offset in the stratigraphy observed in the high wall section, and referred to in the previous section. In places on the north-eastern wall of this fault, the combination of folding (and thrusts) with superimposed faulting meant that the distribution of the targeted coal seams was so complex as to render economic extraction impossible and some areas were simply 'cleaned out'.

The Top Hosie (McDonald) Limestone pavement on the north-west of the SCM and strata in the high wall section are all displaced by two sets of left-lateral, oblique-slip, curvilinear faults with a NNE–SSW and a NW–SE strike (Fig. 10, *opposite*).

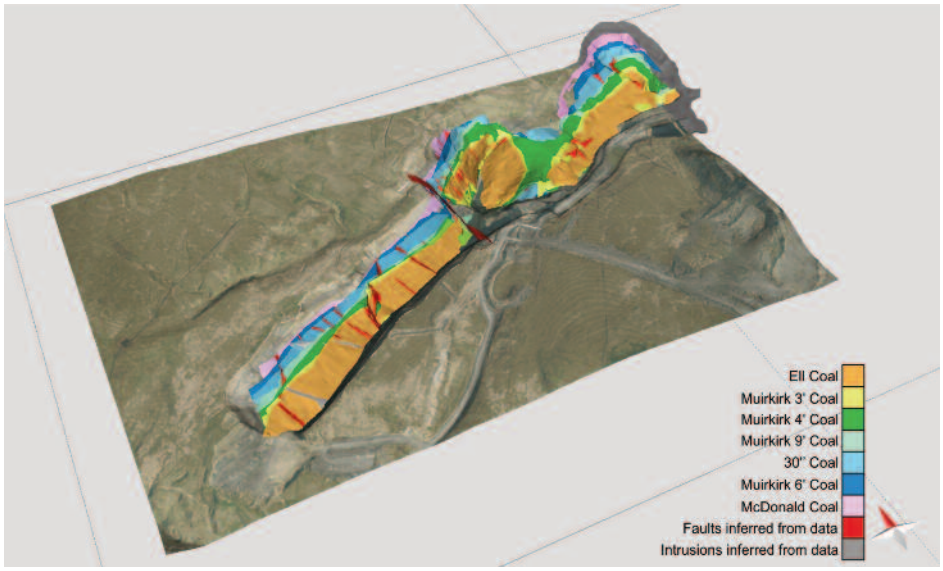


Figure 9 3D model of strata mined from Spireslack main void. Each surface represents a coal seam, and was constructed from geospatial subsurface data. The modelling reveals the complex fold structure that lay within the north-eastern of the site, and which must have posed a challenge for efficient removal of coal during mining operations.

A less prominent set of ENE–WSW striking faults is also present. When viewed in the high wall (*see* Fig. 7), the faults apparently indicate a normal sense of displacement, but it must be noted that there is significant strike-slip movement along these fault planes, as indicated by the clearly striated slickensides and left-lateral sense of faults displacing the bedding plane marking the Top Hosie (McDonald) Limestone (Fig. 11, and inset). Each fault typically has a complex fault damage zone surrounding the fault core with individual fault segments either hard- or soft-linking depending on the scale of relay-ramp breaching (Fig. 11, *overleaf*).

Within the mechanically strong limestone pavement, fault planes are occasionally filled with calcite (multiple generations), and baryte, although cataclastic fault rock is rarely seen. Where fault rock is present, it is a limestone-breccia. When cutting the multi-layered high wall sequence, the fault zones consist of partial clay-smears, brecciated coal and fractured sandstone within the fault core. Mudstones and coals are intensely fractured surrounding the main fault zones and are highly polished on fracture planes. Many faults appear to tip out within the thick mudstone unit overlying the Index Limestone, suggesting a strong rheological control on fault development and propagation. Small metre-scale thrusts are also visible in ironstone layers interbedded with mudstone within the basal Limestone Coal Formation on the north-west wall (Fig. 12, *overleaf*). Combined with the overall folded arrangement of strata within the ENE–WSW striking Muirkirk Syncline, these fault arrays are geometrically and kinematically consistent with an overall pattern of sinistral transpression at this time in the Carboniferous (Leslie *et al.* 2016).

Concluding remarks

Spireslack Surface Coal Mine has the potential to be a national research and learning asset by conserving this large-scale geological site that might otherwise have been lost, along with its relevant digital geological dataset and other social and industrial records. Spireslack can provide a valuable learning experience for the wider public in coal geology, illuminating aspects of a former way of life of previous generations, while also supporting high-quality research into Carboniferous geology. No new opencast developments will likely happen in Scotland, as the last coal-fired power station in the country, at Longannet, was closed in 2016. The window of opportunity to guarantee long-term access to former opencast sites in Scotland will close and so geoconservation is urgently needed.

*Figure 10 View of the faulting affecting the Top Hosie (McDonald) Limestone engineered pavement in the north-west wall at Spireslack SCM, note figures for scale. The dominant features are NN–SSW striking and demonstrate the clear sinistral offset associated with these structures (*see also *Fig. 11).*

Figure 11 Detailed 3D exposure of a NE–SW trending fault zone developed in the Top Hosie (McDonald) Limestone engineered pavement in the north-west wall at Spireslack SCM. The exposure reveals the intricate branching nature of the fault's true architecture, as well as the curviplanar geometry of individual displacement surfaces and numerous relay ramps connecting individual fractures. The gently plunging slickenside lineations, typical of the site as a whole, show the true oblique-slip displacement vector (BGS Photo: 917872).

These ambitions are readily aligned with those of Scotland's Geodiversity Charter, launched in June 2012 and relaunched in November 2017. Scotland's geodiversity is world-class and is the foundation of our ecosystems, delivering essential benefits and services for society. Championed by the Scottish Geodiversity Forum, this Charter for Scotland — the first of its type globally — encourages government, local authorities, companies, organisations and individuals to work together to raise awareness of geodiversity and to integrate geodiversity in policy, decision making and guidance, to deliver well-informed sub-surface planning properly integrated with sustainable management of land and water.

Geology at Spireslack delivers unique man-made exposure on a scale unparalleled in nature; by coming together with colleagues in the Geotechnical and Energy sectors and in universities, BGS and SMRT still seek to promote this hugely rich and diverse resource for learning, research and professional development. Held in trust for future generations, Spireslack could provide that learning platform, combined with a rich visitor experience, especially if supported by and integrated with local community goals as part of a future Geopark. The synergy between natural, cultural and geological heritage is very strong and is best viewed as a complete package.

Acknowledgements

The authors are indebted to the support and encouragement provided by the Scottish Mines Restoration Trust and its Director, Professor Russel Griggs, as we have worked to raise awareness of the geological potential of these sites. In particular, the freely given access to the Spireslack SCM on numerous occasions is greatly appreciated.

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Figure 12 Small-scale thrust faults and localised folding are found in competent ironstone layers within weaker mudstones. Strain is more distributed within the incompetent mudstone.

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Book review

Butler, Barry, and Gunner, John 2017 T*he Coast-to-Coast Walk: Rocks and Scenery*. www.2qt.co.uk: 2QT Limited (Publishing) (ISBN 978-1-912014-52-1; card cover, 287pp; £14.50)

This is a clever book. Its style mimics the famous Alfred Wainwright Pictorial Guides to the English Lake District fells by including numerous 'sketches' and figures. These include walker's views of landscapes, route maps, geological sections, detailed sketches of rock exposures, and cartoons of geological formations to explain the processes described in the text. The cover and general design mimic the Wainwrights (originally published by the Westmorland Gazette, later by Frances Lincoln), but the format is slightly taller and wider, mimicking the more recent 'revised Wainwrights' by Mark Richards (published by HarperCollins). The text, however, is printed rather than the engraved reproductions of Wainwright's hand-written pages.

After his Lake District guides Wainwright worked out a Coast to Coast walk, linking up Public footpaths and Rights of Way across England from St Bees Head to Robin Hood's Bay — *c.* 192 miles — and published this as another 'Pictorial Guide' (Westmorland Gazette, 1973).

Butler and Gunner have organised their book in seven chapters. Although the 'walks' follow the Wainwright C to C routes, the various subsections of each chapter are their own 'a to b' distances along the C to C, interspersed with single location or area 'Journals'. These latter are in blue text, and they describe relevant geological processes and the palaeogeology and palaeogeography.

The seven chapters are logical geographical and geological 'blocks', for the aim of the book is to provide a detailed guide, not to the routes themselves, but to the geology the walker will encounter along the routes. Thus: 1. The West Coast Region, 2. The Lake District, 3. Ravenstonedale, 4. The Yorkshire Dales, 5. The Vale of Mowbray, 6. The North York Moors, and 7. Historical Synthesis of Plate Tectonics. The authors' aim is provide a companion volume for the walker, to explain the geology encountered, and how it came to be. In this aim Butler and Gunner succeed admirably.

Their text is clear and crisp, and can be read with profit by any walker, geologist or other, tackling this great long-distance route. In crossing England using this guide, the rocks and palaeogeology of all those colours on the BGS Bedrock Geology UK North were made much more approachable and understandable to this reviewer. The authors have also included a useful glossary of terms emboldened in the text, to help walkers who may not have heretofore learned so much formal geology. There is also an index.

I walked the Coast to Coast in April 2013 as the first long-distance footpath I undertook upon retirement in December 2012. It is a fantastic walk. When reading this book, the numerous 'walker's views' of the landscape, and also of small geologic details to notice, brought back a wealth of memories — not to mention referrals to my own 'Travels Journal' records of what I had 'noticed'. My only 'regret' is that I wish this book had been published in 2013. I would certainly have included it in my rucksack along with my Wainwright and Trailblazer guides. Whether you walk the whole C to C in one go, in sections, or in day-walks, this book should be in yours!

— Dr David M. Jones, OUGS Proceedings Editor

Book review

Harvey, Adrian 2017 *An Excursion Guide to the Geomorphology of the Howgill Fells*. Edinburgh: Dunedin Press (ISBN 978-1-78046-070-3; paperback, 116pp; £14.99)

While these fells represent one of the most erosionally active landscapes in Britain, the bedrock Lower Silurian geology is described in the introduction as "not particularly striking". However, the Howgill Fells are certainly striking when seen from the M6 and surrounding area. This is an excellent field guide for this remote and interesting area. The author is Professor of Geomorphology at Liverpool University, and has studied and published on this area, and led fieldtrips there, for more than 40 years.

The book is divided in two parts, with the first part describing the geomorphology of the Howgill Fells commencing with a regional overview, then an explanation of the Holocene landform evolution, and finally the modern geomorphic system. Together they privide a good overview and explanation of the geology (briefly), then the geomorphology of the area.

The second part of the book is its main attraction: it describes the field sites*, some of which are certainly remote and hard to access, and for hardy walkers. The first excursion is a reconnaissance road trip around the Howgill Fells; then the following trips cover the area geographically as the western Howgills, the northern Howgills, and finally the southern Howgills. The final reflections set out to answer three key questions, concluding that the Howgills are not typical of other upland areas of Britain due to the intensity of recent erosional processes, but are an ideal field laboratory for geomorphological study as they are as close to a 'natural' landscape as we can get in the UK, along with some of the remoter highlands, and finally Harvey suggests questions for further study in this 'field laboratory', of which there are many.

The book ends with useful appendices on maps, particle sizes, National Grid and GPS co-ordinates for the main sites, references and an index.

A fascinating book on a little-visited area, conveniently situated next to the book town of Sedbergh — an ideal companion for a visit to this fascinating area, highly recommended.

John Lonergan, FGS, BSc OU Geosciences

* *note: Although Harvey does not mention the 'Sedgewick Geology Trail' near Sedbergh, he does describe the sites along the trail. — Ed.*

Edinburgh Symposium 2017: A Festival of Geodiversity
Summing up

Dr Steve Blake, OUGS President

(Senior Lecturer in Earth Sciences, The Open University)

Firstly, I thank Michael Perkins and his organising committee for putting on the third Edinburgh Festival – the OUGS 'Festival of Geodiversity'. Scotland is renowned for packing an enormous amount of geology into a relatively small geographic area, so this year's [2017] symposium theme was aptly chosen. The strong programme of talks lived up to expectations, as we ranged from the Precambrian to the present, from zircon dating to engineering geology and to geological conservation. Many of the talks melded diverse approaches to a given set of rocks with, for example, sedimentology and evolutionary biology, or stratigraphy and structural geology, being combined to solve problems or bring a new, more holistic, appreciation of the geological past.

On the first evening, Simon Cuthbert gave a brilliant tour through the rocks, geological history, and economic geology of the Scottish Southern Uplands. While the rocks exposed at the land surface give the geologist a view of a 3D body of crust formed by plate tectonic and surface processes, many of the mineral deposits were formed by the passage of later fluids through those rocks. The sources of the fluids are typically not visible. In some cases fluids moved up from plutonic rocks that still sit at depth, with no surface outcrop, but which can be divined by geophysics. Or, the fluids moved downwards from shallow but now eroded and vanished rocks.

Maarten Krabbendam explained his recent work on the famous rocks of the NW Highlands – The Torridonian (sandstones, beloved of sedimentologists) and the Moine (quartzites, beloved of structural geologists). Maarten showed, through a combination of field mapping and radiometric dating of zircon and rutile, that much of the Torridonian and Moine are expressions of the same denudation and depositional events associated with the Grenville Orogen. Rather than being unrelated rock units, the Torridonian and Moine had a common origin before following different paths.

Tim Kearsey described the recent discoveries, of world importance, of the earliest terrestrial tetrapod fossils, dating from the early Carboniferous of the Scottish Borders. Not only are the fossils a palaeontological treasure trove, but the rocks containing them reveal much about the environmental conditions in which these creatures adapted and evolved. The recent spread of land plants was one of the keys, as this had created sediment and soil stabilisation with consequences such as the establishment of meandering river systems — novel environments that these new evolving tetrapods were able to take advantage of.

Paul Mellon told us about the work of geologists in the design and construction of the Queensferry Crossing (the 'new Forth Road Bridge'). While it is easy to think of these massive construction projects in purely engineering terms, Paul led us through the process of design and construction, to show how geologists played an essential role in bringing this modern piece of infrastructure to fruition. Geologists were key to the foundation phase of the project and, unlike most geologists, were in the enviable position of being able to create new exposures and repeatedly check assumptions and interpretations as excavations continued.

Our geological travels through space and time then took us to the Isle of Skye, an island microcosm of geodiversity. Neil Clark reported on exciting new dinosaur finds of international importance from the Middle Jurassic of Skye. This was a time of significant dinosaur diversification but for which fossils are rare, meaning that the new finds in Skye are filling gaps in knowledge. These skeletal fossils (as well as fossil footprints) reinforce Skye's reputation as a leading geological site. Neil happened to mention that about 1,000 dinosaur species are known globally. That fascinated me. The number of mammal species at the present time is five times higher, and bird species numbers are an order of magnitude greater. Although the fossil record is unavoidably biased and under-sampled, the species count for a group of animals with a 170-million-year-long 'reign' seemed surprisingly small to me. In any case, connections between species numbers, organism size and length of presence in the geological record provide much food for thought. Perhaps the Isle of Skye may yield a new dinosaur species to add to the tally.

Many aspects of geology resonate with the public whether by fuelling the imagination in the case of dinosaurs, or, as with hydrocarbon exploration and 'fracking', by impinging on our economic well-being. The Midland Valley of Scotland has long been a source of fossil fuel and most recently has come into focus as a target for hydraulic fracturing to extract shale gas. Taking a tour along the East Lothian coast to trace the story of sedimentation and structural deformation of the Midland Valley, John Underhill explained how possible targets in the Midland Valley and elsewhere in the UK experienced deformation, which has led to some hydrocarbons escaping and/or the reservoirs becoming so highly deformed as to render the prospects for efficient extraction less than ideal. The assumption that UK shale gas lies in geological conditions similar to those of successful extraction projects overseas turns out to be flawed, with our unconventional hydrocarbon resources having largely missed their 'extract by' date by some 55 million years.

The terrestrial volcanic and sedimentary rocks of the Hebridean Igneous Province were the topic of Ian Williamson's talk. Although some 61 to 57 million years old, these rocks, exposed in the Inner Hebrides, preserve fascinating detail of lava flow structures and evidence for lava–sediment interactions that compare well with details seen in modern settings such as Iceland. Ian's talk provided another case study of how diverse geological tools ——volcanology, stratigraphy and palaeoenvironmental analysis — combine to reveal a picture that is richer than the individual parts.

David Jarman showed us how many mountains in the Scottish Highlands bear the scars of rock slope failures This was a new discovery for me and a classic case of 'obvious' dramatic landscape features becoming visible only after getting one's eye in. Trips to the Highlands will never be the same again. These features formed after the retreat of glaciers, and at least some may be responses to the removal of the support given to glacially carved valley sides. The youngest failure to have been dated

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happened some 1,800 years ago, in Glen Coe. Are there more still to happen?

The final two talks of the symposium related to initiatives within the Midland Valley, related to educating the public about geology. Rosalind Garton described the many activities and accomplishments of geoHeritage Fife. As well as encouraging the public to see geologically interesting and significant sites for themselves, by publishing guides for self-guided walks, geoHeritage Fife also bring geologically significant sites to the attention of local planning authorities in an attempt to save them from being damaged or destroyed by unwitting 'improvements'.

Graham Leslie described the geology of the disused Spireslack opencast coal mine in East Ayrshire and the potential for turning this enormous site of near-100% 3D exposure from an industrial scar into a future Geopark. Whereas other abandoned opencast mines have been filled in and their potential as teaching and research centres lost, the aim is that Spireslack can be developed into a hands-on resource for future generations, not just to appreciate social and industrial heritage, but to discover the 3D nature of geology, and become a site for industrial and academic training in Carboniferous Coal Measures geology.

The symposium speakers showed how Scotland's geology has something for every interest, and much that is new to science or that is relevant to the present. I thank them for sharing their knowledge, insight and experience in a series of clear and engaging talks that inspire us all to look forward to the next annual OUGS Symposium.

An alternative model of plate tectonics*

Françoise Chalot-Prat[1] and Elisabeth d'Eyrames[2]

[1]Centre de Recherches Petrographiques et Geochimiques, Lorraine University,Vandoeuvre-les-Nancy, France
[2]Open University Geological Society, Mainland Europe Branch

* originally published in *€urock The Electronic Newsletter of The Open University Geological Society, Mainland Europe*, Winter 2017, 1–5 — Ed.

Introduction

Françoise Chalot-Prat, our leader during the mapping week in the Ardèche, has recently been researching lithosphere and asthenosphere interactions at ocean ridges in the framework of the westward drift of plates, in collaboration with C. Doglioni (Italia) and T. Falloon (Australia).

They combine geophysical, structural and petrological data to support an alternative model for oceanic plate spreading. The results of their research have been published in *Lithos* (Chalot-Prat *et al.* 2017). A synthetic slide presentation, including figures from previous papers, is available on the website mantle-plumes.org). This fairly new model of the 'westward drift' as a driving force of plates intrigued us all, and eventually we got Françoise to give us a presentation on the last afternoon of our mapping week. So we all gathered at the bar, where Françoise gave us an off-the-cuff presentation about this research. Here is the transcription of it:

An alternative model

Following Alfred Wegener's (1915) continental drift, the theory of plate tectonics was introduced in 1968 to the scientific community and was accepted three years later. The theory was based on tectonic lithospheric plates composed of crust and uppermost mantle, moving over or descending into the asthenosphere or deeper.

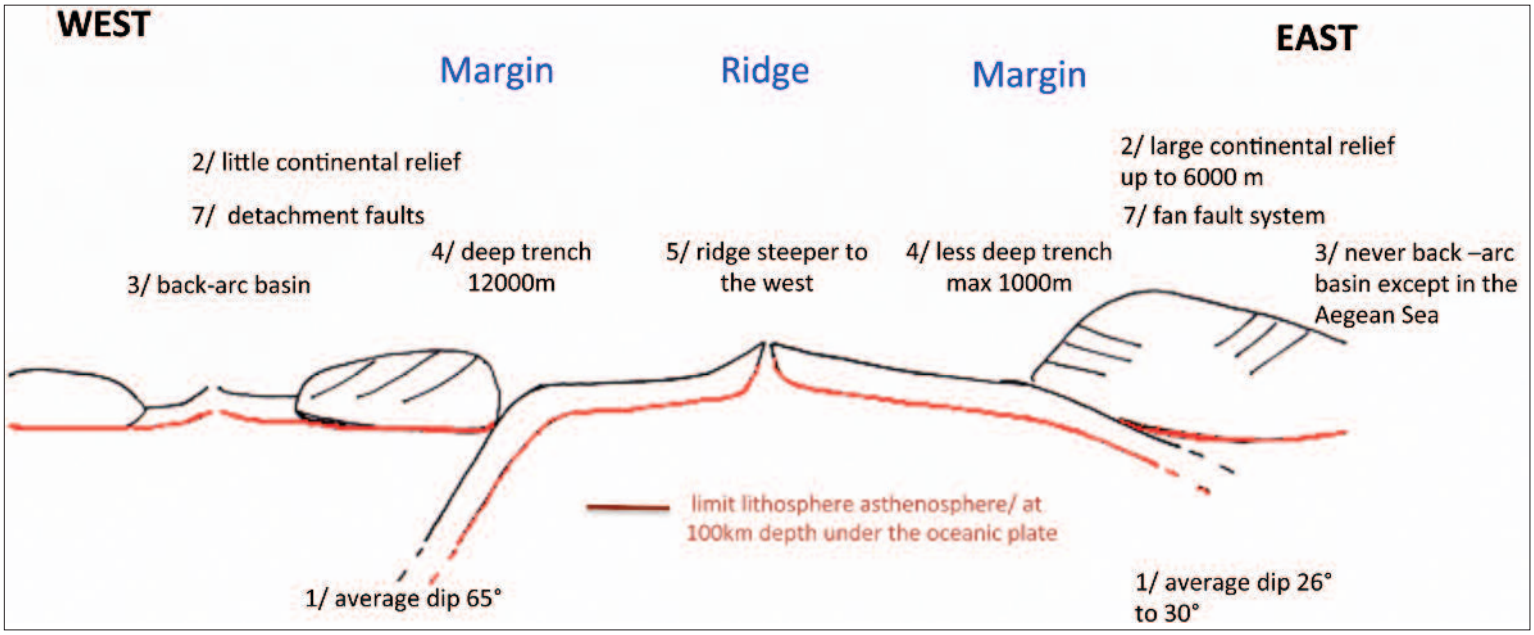
W. J. Morgan (1971, 1972) published the following idea: mantle convection is moving the plates and transfers matter within the mantle and, accordingly, the model of mantle plumes. It was only an idea without any observations supporting it.

The hitch is that convection cells are symmetric and symmetry is not observed in plate tectonics. The first to observe asymmetry was Carlo Doglioni when he was working on geophysical data around the world. His first paper was published in 1990 (The global tectonic pattern). As the model of convection cells does not support asymmetry, he also presented another model for plate tectonics (Doglioni 1993; Doglioni *et al.* 1999, 2003, 2007).

For example, when observing a cross section through oceans framed by subduction zones like the Pacific Ocean a number of asymmetries can be listed (Fig. 1).

1. The dip of the slope of the oceanic slab subducting westward is on average of 65° and eastward only 30° on average. These observations also concern subducting continental slabs in collision zones (for example, in the Alps and in the Apennines).
2. On the western margin, there is little continental relief, whereas on the eastern margin there is a large continental relief that can reach 6000m in altitude.
3. Back-arc basins form west to a western margin, which is rarely the case east to an eastern margin (the Aegean Sea is an exception).
4. The subduction trench is far deeper in the west (up to 12,000m) than in the east, where it reaches 1,000m; and there is more sediment accumulation in the west.
5. The slope of the western side of an ocean ridge is always steeper than on its eastern side.
6. The fault system within the orogen on each side of the ocean is different. On the western margin, the orogen is mainly crosscut by major west-dipping faults (simple vergence system), whereas the orogen on the eastern margin is crosscut by a double vergence system (east-dipping faults to the west and west-dipping faults to the west).

Figure 1 List of asymmetries that can be observed on a cross section through oceans framed by subduction zones similar to the Pacific Ocean.


WEST
EAST
Margin
Ridge
Margin
2/ little continental relief
7/ detachment faults
3/ back-arc basin
4/ deep trench 12000m
5/ ridge steeper to the west
4/ less deep trench max 1000m
2/ large continental relief up to 6000 m
7/ fan fault system
3/ never back –arc basin except in the Aegean Sea
limit lithosphere asthenosphere/ at 100km depth under the oceanic plate
1/ average dip 65°
1/ average dip 26° to 30°

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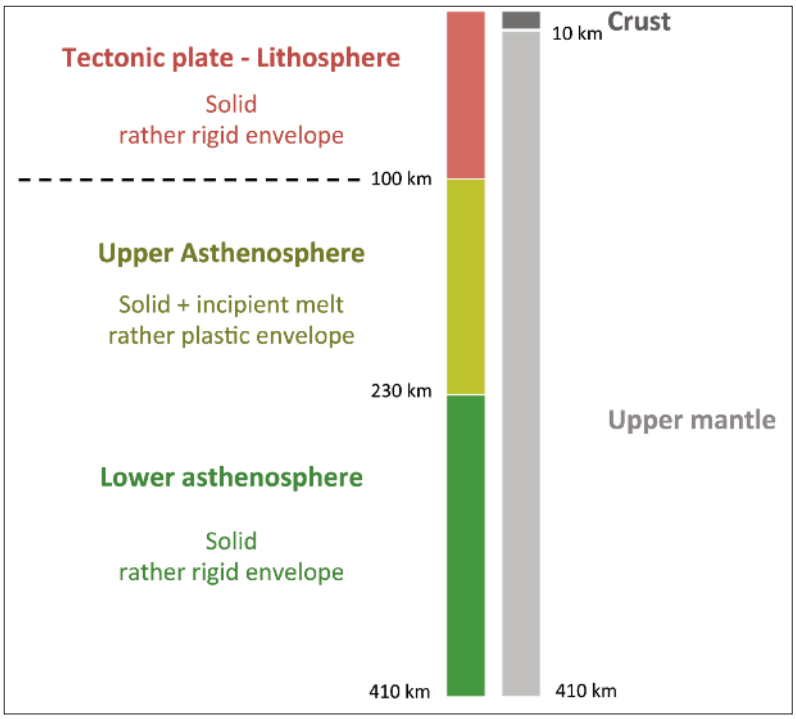


Figure 2 Rheology and thickness of the lithosphere and the asthenosphere below oceans.

The cause of plate tectonics cannot be one that produces symmetrical features like convection. Therefore Doglioni proposes another explanation: "The movement of the plates is due to the rotation of the Earth counteracted by the rotation of the Moon." (Doglioni 1990, 1993; Scoppola *et al*. 2006).

The rheology of the lithosphere differs from the uppermost part (100–230km) of the asthenosphere (Fig. 2); the lithosphere is solid and rather rigid, whereas the uppermost part of the asthenosphere has a plastic behaviour because it is a solid with incipient melt, as we know from geophysics and experimental lab research.

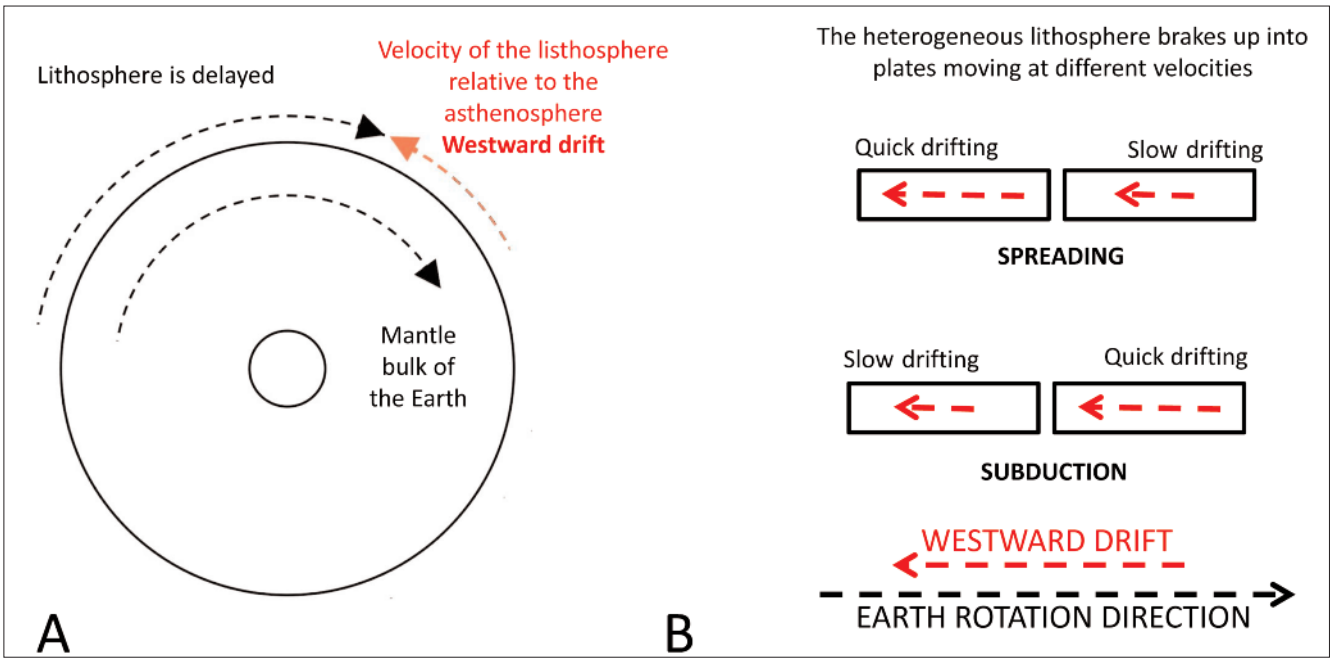
The bulk of the Earth (mantle) rotates eastward (Fig. 3A). The lithosphere, which is more rigid (or viscous), rotates at a slower speed and thus lags behind. To help to grasp this model and reason with it, Doglioni (1993) proposed the concept of 'westward drift of the lithosphere'; instead of speaking about the lithosphere lagging behind the mantle, he considers the relative movement of the lithosphere to the asthenosphere, which is a drift to the west. Besides, the lithosphere is heterogeneous, so that its whole rigidity varies significantly from place to place. The different parts have thus different velocities and the lithosphere fragments into different plates. When the western part of a plate drifts faster towards the west than the eastern part, spreading occurs. If the western part of a plate drifts more slowly to the west than the eastern part, subduction occurs (Fig. 3B). The more a plate is rigid, the more it lags and the faster it drifts to the west.

Now, how can previous asymmetries observed across an ocean bordered by subduction zones be explained with this concept?

On Figure 4 *(opposite)*, the western subduction zone can now be read as a slow drifting plate (margin) followed eastward by a quicker drifting plate (subducting slab). The asthenospheric flow pushes the slab downward and conversely, on the eastern side of the ocean, the asthenospheric flow prevents the plunge of the slab. The high velocity of the sub-vertical westward-subsiding oceanic plate, always higher than the sedimentation velocity, explains the deep western trench and the great thickness of accumulated sediments. The high relief on the eastern margin is explained by the intense shortening of the continental lithosphere as it is blocked by the slower oceanic plate that plunges beneath it.

In continental settings, when the western continental plate drifts slower than the eastern continental plate, similar asymmetrical features are observed: deep trenches, steep subducted slab and moderate margin are observed.

Figure 3 A, Definition of the 'westward drift' model on a cross section of the Earth at the equator, view from the North Pole; B, spreading and subduction in the westward drift model.



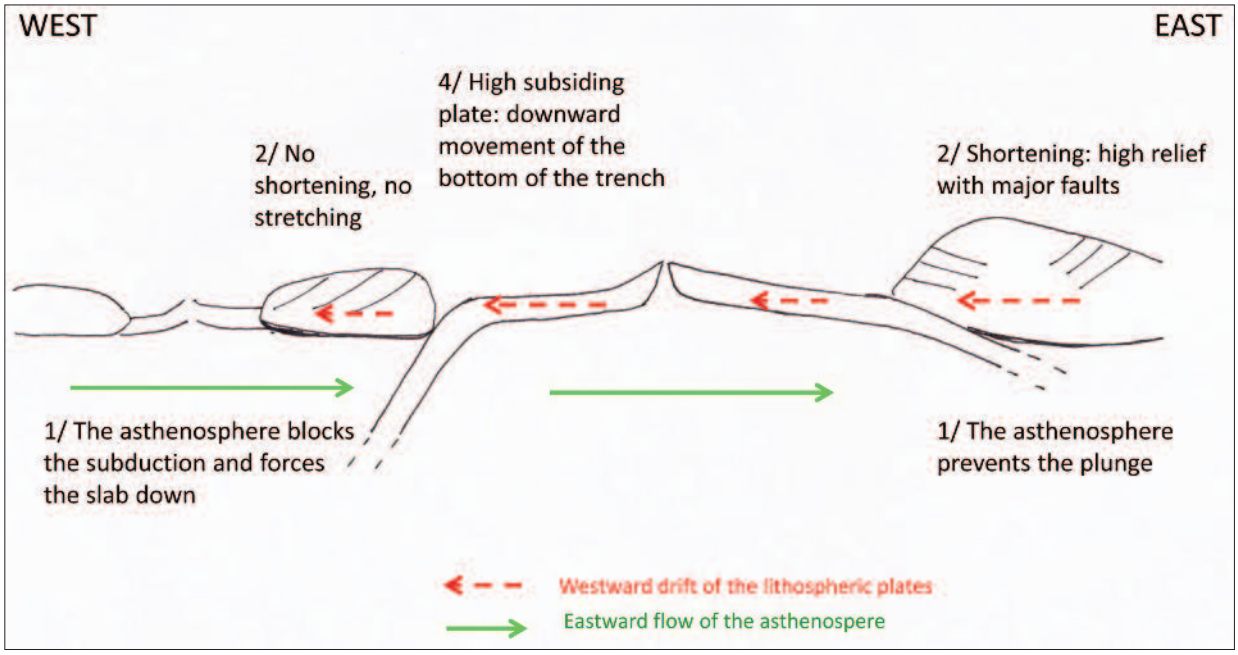

WEST
EAST
4/ High subsiding plate: downward movement of the bottom of the trench
2/ No shortening, no stretching
2/ Shortening: high relief with major faults
1/ The asthenosphere blocks the subduction and forces the slab down
1/ The asthenosphere prevents the plunge
Westward drift of the lithospheric plates
Eastward flow of the asthenospere

Figure 4 The asymmetries observed in the context of the westward drift of the lithospheric plates.

In return, high margin relief and subducted slab with low slope are observed in east-dipping subduction contexts. This process is illustrated by the following examples. In Romania, south-east of the Carpathian Mountains (rising up to 2,600m), the Focsani Basin is the result of the north-west subduction of a continental plate below the Carpathian plate. This subduction started 10Ma ago and accumulated 8,000m of sediments that produced oil and gas. In Italy, the Apennines (rising up to 2,900m) are a collision zone, where the faster-drifting north-east plate subducts under the south-west plate with a dip of 80°. In the Alps, the European plate plunges south-eastward at an angle of 30° below the Adriatic plate, with many summits above 4,000m (rising up to 4,800m).

In addition to these observations of asymmetrical structures, geophysics show that the oceanic eastern plate has less thickness, lower density and less rigidity than the western plate. It can be explained by significantly different growth conditions of the western and eastern plates, inducing sensibly distinct mantle thickness and composition from one plate to the other on each side of the ridge axis.

When considering what happens during ocean spreading within the westward drift model, the scenario can be devised as follows (Fig. 5, *overleaf*):

(a) At the spreading axis (Fig.5 t1), the asthenosphere ascends and undergoes partial melting, leading to formation of a basaltic magma and a Fe-depleted residual mantle. The residue, less dense than its protolith, accretes to the base of the overlying lithospheric mantle (minimum of 30km in thickness at the ridge axis), while the pressurised magma percolates upward either very quickly to give basaltic volcanoes on the ocean bottom, or slowly in between mantle minerals with which it reacts (metasomatism and mantle refertilisation). So one way or another during spreading, the lithospheric mantle thickens. This leads to the following questions: Why is there less thickening eastward of the ridge axis? And why are mantle compositions slightly different in the western and eastern plates?

(b) As the spreading ridge migrates with the westward drift, the asthenospheric partial melting zone below the ridge migrates with the westward drift too. The effects are necessarily different on either side of the ridge axis. Indeed the ridge migration velocity (Vr) is always higher than the half-spreading velocity (hS) (see equations on Fig. 5). This means that the eastern limb of the ridge axis is progressively abandoned eastward, whereas the western limb of ridge axis stays above the melting zone for a while, depending on the spreading rate. At t2, then t3 (Fig. 5), residues progressively accumulate against and partly on each other at the base of the western limb, whereas residues are scattered at the base of the eastern limb.

(c) The western limb thickens faster and more significantly than the eastern limb. In doing so, the western mantle plate is strongly Fe-re-enriched and refertilised by metasomatism. It becomes denser and more rigid (Fe has the highest modulus of rigidity) than the eastern plate.

(d) The eastern limb is much less metasomatised and refertilised. It is less dense than the western one, and the isostatic compensation induces a higher uplift of the eastern limb and a slope asymmetry of both sides of the ridge.

Concluding remarks

These are, schematically, the basic features of the alternative model for understanding the growth of an ocean. There were many questions about this alternative model of plate tectonics, so that for further reading Françoise forwarded us a list of papers supporting the observations on asymmetry of the Earth.

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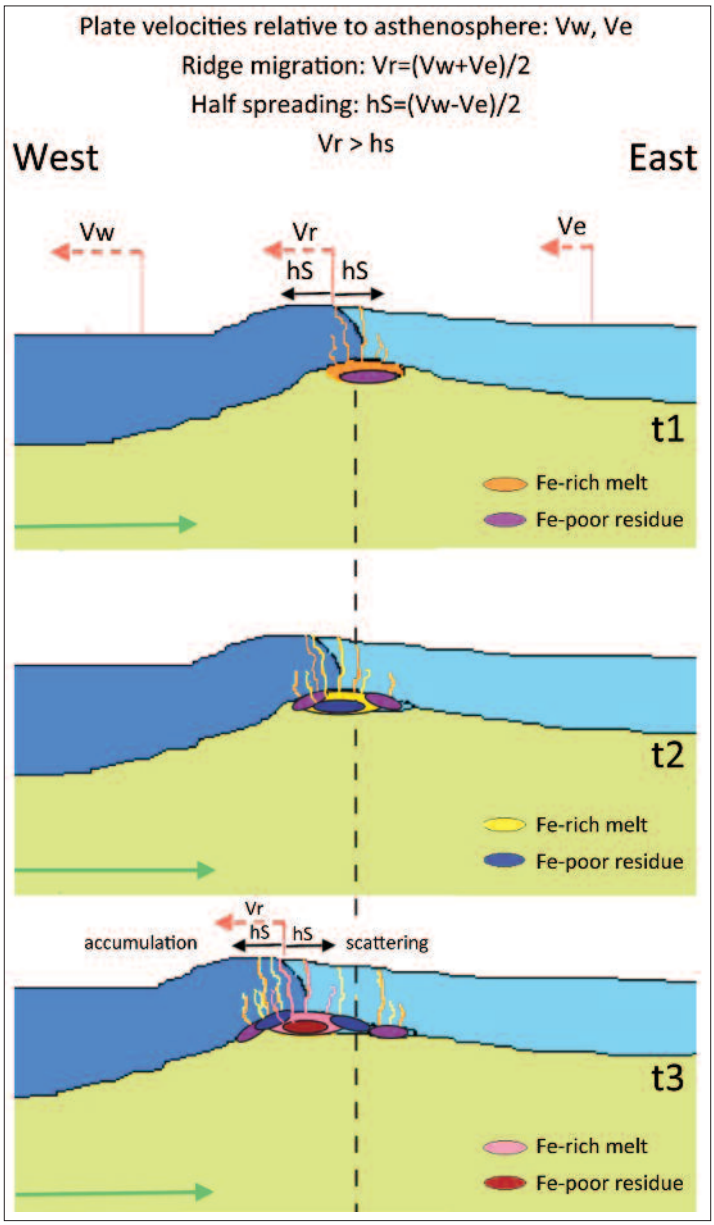

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Figure 5 How to build asymmetric plates on both sides of a spreading ridge? Oceanic spreading is synchronous with westward drift of lithosphere above asthenosphere. The half spreading rate hS on both sides of the ridge is lower than the ridge velocity Vr. Starting with t1 being the initial situation, t2 and t3 show how in time each limb on each side of the ridge axis acquires mantle thickness, composition and morphology sensibly different from the other.

A short note on the El Hoyazo 'crater', Almería province, south-east Spain

Duncan Woodcock

Introduction

El Hoyazo is a prominent crater-like feature approximately 1km across and located 3km east of the town of Nijar in Almeria province, south-east Spain. Despite its superficial resemblance to a volcanic crater, it was not produced as the result of an explosive eruption. The crater rim comprises a limestone escarpment of Messinian (upper Neogene) age (Mather *et al.* 2001). Exposures inside the 'crater' are of an igneous rock that has been brecciated and pervasively altered. This rock is notable for its unusual composition and for an abundance of xenoliths. The igneous activity at El Hoyazo is related to a wider province of Neogene calc-alkaline volcanic activity in south-east Spain (Mather *et al.* 2001).

Field guide

El Hoyazo can be accessed by following either of the tracks that run east from the Nijar road, immediately to the north-west of motorway junction 481 (Fig. 1). A *rambla* (dry stream bed) cuts through the south-south-east side of the crater and provides access to the interior. A convenient place to start exploration is the location where the *rambla* crosses the more northerly of the two tracks. Figure 2 comprises a large-scale map of El Hoyazo that was developed from the Google Earth image used as a base map during my visit in 2015.

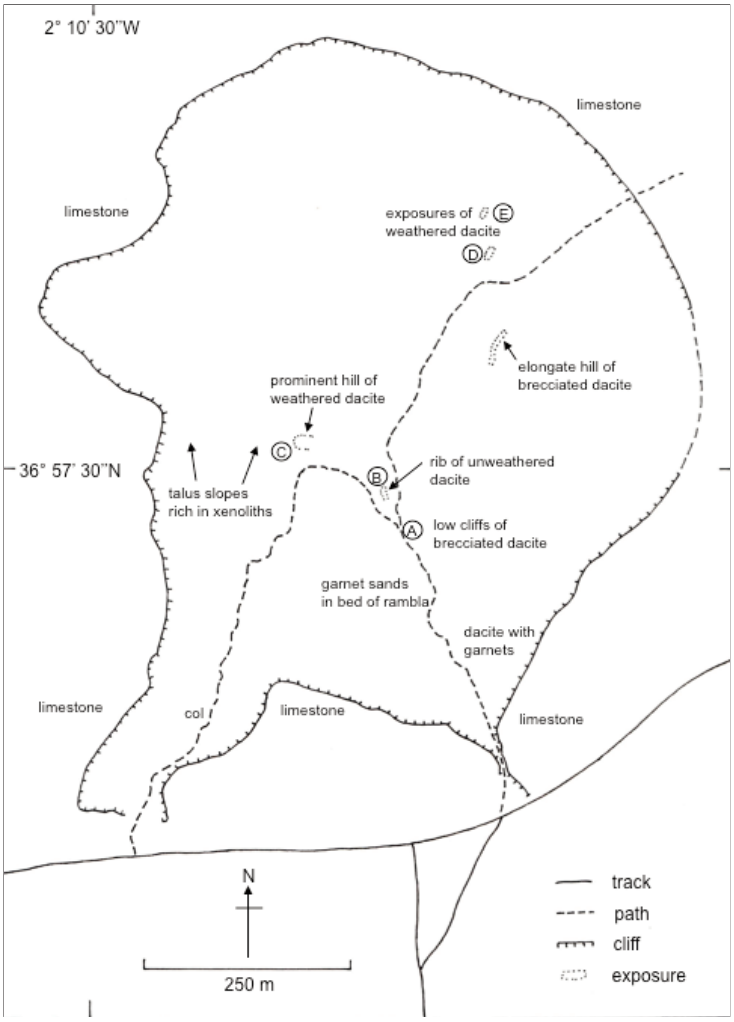

Figure 2 Large-scale map of El Hoyazo, showing the main rock exposures within the 'crater'.

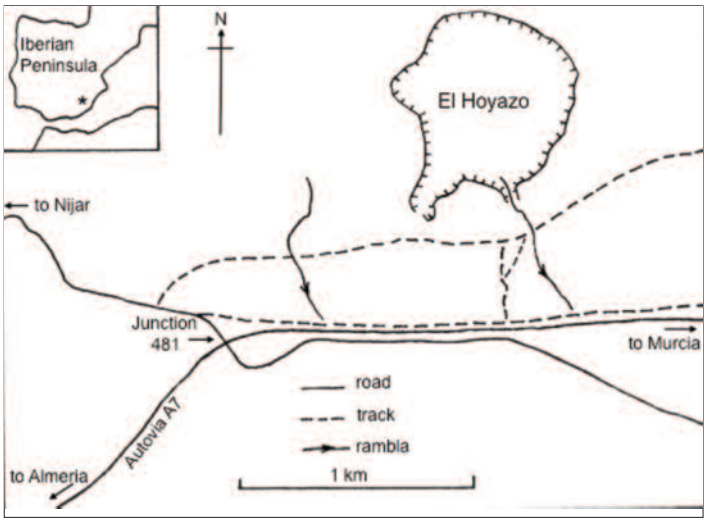

Figure 1 The local area around El Hoyazo. The asterisk on the inset map shows the location of El Hoyazo in Almeria province.

A path follows the *rambla* north-north-west uphill into the crater. Reddish garnets, typically 1–3mm in size, can be seen at several places forming a sand in the bed of the *rambla* (Fig. 3). Initially, most of the boulders in the *rambla* are of limestone; however, boulders of a grey, fine-grained igneous rock with prominent garnets become increasingly common upstream. About 100–150m up the path from the track there are *in situ* exposures of this rock with garnets weathering proud of the surface. Petrographic studies showed this rock to be a dacite with an unusual composition (Zeck 1970).

Figure 3 Garnet sand in the bed of the rambla *that cuts into the side of the El Hoyazo 'crater' (coin is* c. *20mm in diameter).*

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Figure 4 Brecciated and pervasively altered dacite at Location A, 36° 57.453′ N 02° 10.216′ W (black hammer handle is 120mm long).

At location A in Figure 2 the gradient of the path decreases and the *rambla* passes through low cliffs of dacite that has been brecciated and pervasively altered (Fig. 4). Immediately beyond location A, the passage widens out to give a view across to the limestone escarpment on the opposite side (Fig. 5). Much of the exposure within the crater is of variably altered dacite; however, a small exposure at Location B appears to be unaltered (Fig. 6, *opposite*). This material is medium to dark grey with conspicuous garnets and black flecks of biotite (Fig. 7, *opposite*).

A prominent hill at Location C comprises altered dacite rich in xenoliths that weather proud of the surface (Fig. 8, *opposite*). Most of these xenoliths contain garnet and biotite, together with white, wispy patches. Figure 9 *(opposite)* shows a close-up view of a fresh surface of one of these xenoliths. A talus slope on the north-north-west side of the hill contains an abundance of garnet crystals and xenoliths that have been liberated from the altered dacite by weathering. There are additional exposures of altered dacite to the north-east at Locations D and E. In particular, at Location E the dacite has several large xenoliths of a garnet-biotite gneiss (Fig. 10, *page 108*).

The limestone escarpment can be accessed by following the path that runs south-south-east from Location C to just beyond the highest point ('col' on Fig. 2). An itinerary that examines this limestone, together with additional exposures immediately to the west of El Hoyazo is presented in Mather *et al.* (2001).

Petrography

Dacite

In hand specimen (*see* Fig. 7) the unaltered rock is medium grey with prominent reddish-purple crystals typically 3–5mm in size. The rock has a crystalline texture with no preferred orientation and appears to be slightly porphyritic with a fine-grained groundmass. The reddish-purple crystals display fractures but no cleavage,

Figure 5 View west from Location B, 36° 57.503′N 02° 10.254′ W, showing part of the limestone escarpment that forms the rim of the 'crater'.

Figure 6 Small exposure of unaltered dacite at Location B.

consistent with garnet. The other visible minerals present are black biotite, grey glassy quartz and a white mineral with one good cleavage — probably feldspar. The patches of fine-grained groundmass appear almost glassy in darker hand specimens.

A thin section confirms the identification of garnet, brown pleochroic biotite and irregular grains of quartz. Plagioclase feldspar occurs as tabular crystals with cores full of inclusions and clear rims. The groundmass is very fine-grained and almost glassy in places. Zeck (1970) records a similar mineralogy, but with the addition of cordierite. This could not be identified in thin sections of unaltered dacite; however, in sections made from more altered dacite some low-relief areas appear yellowish in patches, consistent with the alteration of cordierite to pinite (Deer *et al.* 1966).

Xenolith

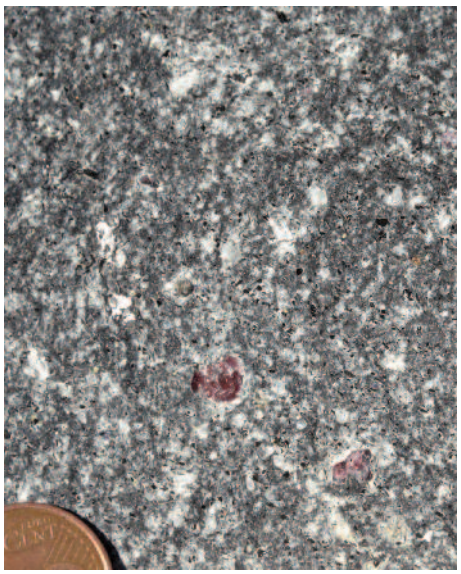
In hand specimen (Fig. 9) the unaltered rock is medium grey and mottled with prominent reddish-purple garnets similar to those in the dacite. The rock appears to have a coarse grained crystalline texture with a foliation. In addition to garnet there appear to be three minerals present: black biotite, light grey feldspar and a mineral occurring as white, wispy patches.

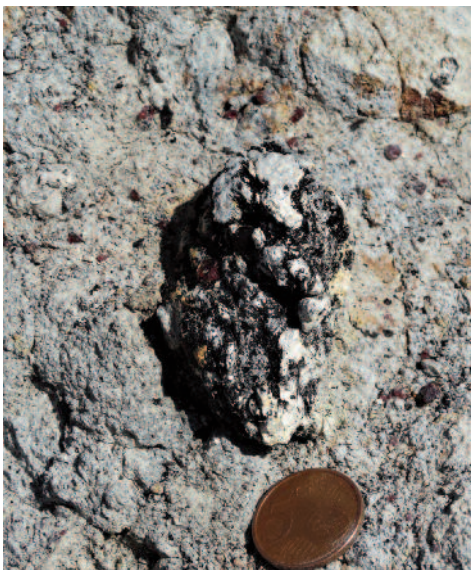
A thin section confirms the identification of garnet, brown pleochroic biotite and lamellar-twinned plagioclase feldspar. The white, wispy patches comprise a fibrous mat of elongate crystals that show up to first-order red interference colours between crossed polars and are length slow, suggesting that the mineral is fibrolitic sillimanite (Deer *et al.* 1966).

Figure 7 (below, left) Fresh surface of unaltered dacite at Location B.

Figure 8 (below, centre) Xenolith of gneiss weathering proud out of altered dacite at Location C, 36° 57.537′ N 02° 10.312′W.

Figure 9 (below, right) Detailed view of a xenolith in altered dacite at Location C, showing reddish garnet and black biotite together with white patches that contain fibrolitic sillimanite. The xenolith was broken parallel to the foliation to expose the fresh surface shown (field of view 40mm × 30mm).





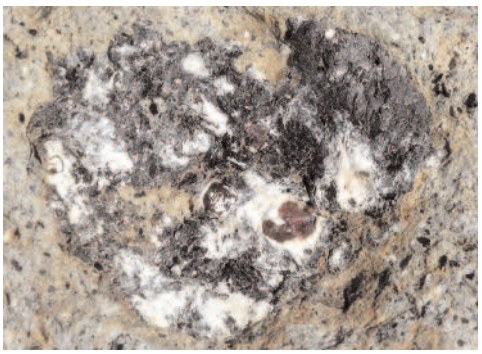


Figure 10 Large xenolith of garnet-biotite gneiss in weathered dacite at Location E, 36° 57.706′ N 02° 10.152′ W (coin is c. *20mm in diameter).*

Geochemistry

Table 1 *(below)* contains a representative chemical analysis of the dacite, together with the corresponding CIPW normative mineralogy. The analysis plots at the high alkali end of the dacite field on the total alkalis versus silica (TAS plot) (e.g. 6.1 in Gill 2010) and can be identified with a high-K association when plotted on a K_2O vs SiO_2 plot (e.g. 6.11 in Gill 2010).

The normative mineralogy shows that the dacite is corundum-normative. The dacite is thus peraluminous, with an excess of Al_2O_3 over that needed to combine with Na_2O, K_2O and CaO to produce feldspars. This excess produced the Al_2O_3-rich minerals (almandine garnet and cordierite) seen in the thin sections.

Petrogenesis and land-form development

The unusual composition of the El Hoyazo dacites was produced by some degree of crustal assimilation by a calc-alkaline magma (Zeck 1992). Cesare *et al.* (1997) provide mass balance calculations that suggest 20–30% partial melting of semi-pelitic rocks at 850°C and 5–6kbar, and consider that the abundant biotite-garnet-sillimanite gneissic xenoliths represent the restite from this partial melting.

By analogy with the more extensive calc-alkaline magmatism farther south in the Cabo de Gata volcanic province, Mather *et al.* (2001) consider that the El Hoyazo dacite was extruded as a dome below or near sea level. Magma–water contact would have promoted pervasive brecciation and alteration of the outer carapace of the dome. On cessation of igneous activity, Harvey and Mather (2015) envisage the development of a fringing reef around the volcanic edifice. Subsequent differential erosion resulted in removal of the altered and fractured dacite and inversion of the topography leaving a 'crater' rim of more resistant limestone.

Appendix: note on the latitude and longitude data

The latitude and longitude of each location were determined with a Garmin eTrex hand-held GPS unit, set to the WGS 84 map datum, with a minimum of six satellites in view. In all cases the error displayed was less than ±10m, corresponding to ±0.005′ of latitude. The third decimal place in the minutes values recorded is thus probably not significant.

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Table 1 Chemical analysis and normative mineralogy for El Hoyazo dacite

chemical analysis from Table 2 in Zeck (1970)[a]		CIPW norm, calculated via Lowenstern (2000)	
oxide	*weight %*	*normative mineral*	*weight %*
SiO_2	65.9		
TiO_2	0.70	quartz	27.9
Al_2O_3	17.7	corundum	5.83
Fe_2O_3	0.69	orthoclase	21.8
FeO	4.32	albite	19.3
MnO	0.09	anorthite	11.3
MgO	1.90	hypersthene	11.1
CaO	2.55	magnetite	1.00
Na_2O	2.29	ilmenite	1.34
K_2O	3.68	apatite	0.50
P_2O_5	0.22	*total*	100.0
total	100.0		

[a] recalculated on anhydrous basis

Dendritic exsolution structures in an olivine from Fuerteventura

Julian Overnell

(Fashven, Musdale Road, Kilmore by Oban, Argyll PA34 4XX, UK)

Summary

A black, coarsely crystalline olivine pyroxenite from Fuerteventura, Canary Islands, when viewed optically in thin section contains many unusual black dendritic structures within the olivine crystals. These appear to be flat, and when viewed in plan resemble cartouches. When viewed nearly edge-on, an intimately associated accompanying phase is also seen. This appears bright white between crossed polars (XPL), which would be not inconsistent with quartz.

Introduction

The volcanic island of Fuerteventura is in the Atlantic off the coast of Morocco. Field guides to the geology have featured in the *OUGS Journal* (Woodcock 2000, 2009), in Carracedo and Day (2002), and in Muñoz *et al.* (2003).

Dendritic exsolution structures in olivine have been reported in the past, both in fayalite-rich and fayalite-poor olivines, e.g. Putnis (1979), Moseley (1984) and references therein, and Khisina and Lorenz (2015). Recently, Teagle *et al.* (2012) have reported similar structures within an olivine in an olivine gabbronorite encountered in an International Ocean Drilling Program cruise. These dendritic structures are not common, but they have been reported over a number of years. Electron microscopy with electron microprobe analysis has shown the structures examined to have been planar structures comprising an intimate mixture of spinel (principally magnetite) and clinopyroxene (see Moseley 1984, and Khisina and Lorenz 2015).

Materials and methods

The sample, loose, is from about half way along a track and dried-up river bed (or *barranco*) from Alto de Aguaje to Playa de la Solapa, west of Pajara, Fuerteventura *c.* UTM 28R 0583,3137. It was black in hand specimen with cm-scale crystals. It was not in context, although there were a few other similar-looking rocks in the vicinity in the *barranco*. They had presumably been washed to their present location during the most recent flood.

The sample was sawn, ground flat with 800-mesh Carborundum, glued to a microscope slide with Petropoxy, and then finally reduced to 30µ with 800-mesh grit. A cover slip was affixed with Canada balsam. Thin sections were viewed using a polarizing microscope and photomicrographs were made using an iPad, looking into the vertical eyepiece of the trinocular head.

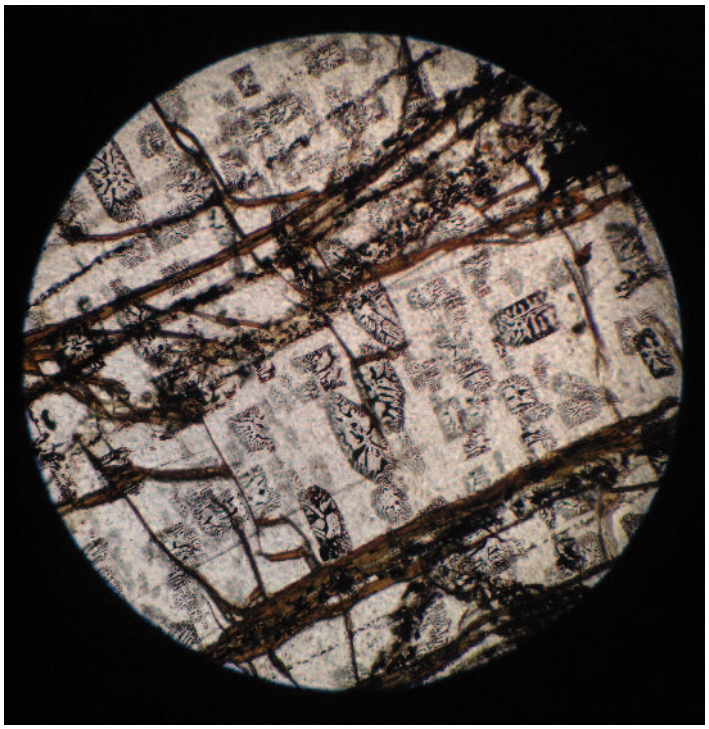
Results

In thin section the sample is seen to comprise cm-scale clinopyroxene, *c.* 75%, and lesser olivine, *c.* 25%. The clinopyroxene shows zoning in PPL with respect to its brown colour and also with respect to the extinction position in XPL. There are some minor bands of alteration. The olivine crystals are smaller, up to *c*. 7mm long, usually with an irregular, rounded outline — although in one case an olivine had a hexagonal outline. They have wide fracture lines typical of olivine. The olivine is biaxial with a 2V of *c.* 90°, and so it is assumed to comprise mainly forsterite with only a minor fayalite content. All olivines in the section show dark internal structures; in some cases these are narrow and in other cases wide, roughly rectangular. Figure 1 is a photomicrograph in PPL of part of an olivine crystal showing wider, rectangular dendritic structures usually denser at the margin, which makes them reminiscent of cartouches.

The structures appear thinner than the section (30µ) because as the focus is adjusted different parts go in and out of focus owing to the limited depth of focus of the ×20 objective. Thus, the slightly fuzzy parts in the photomicrograph are only fuzzy because these parts are slightly out of focus. The background olivine shows a slightly mottled appearance. In XPL the birefringence colour of the olivine goes into uniform extinction both outside and within the cartouches as the stage is rotated. In this view there is no indication of any other component visible in transmitted light accompanying the opaque structures. However, if these structures are viewed (almost) edge-on (in another olivine crystal) another phase can be seen. Figures 2 and 3 *(page 111)* are photomicrographs of an olivine where the dendritic structures are now being viewed nearly edge-on.

In XPL, Figure 3 shows a thin, colourless mineral with first-order white birefringence in close association with the black dendritic structures. Again it is not possible to obtain a sharp image owing to the oblique section and the limited depth of focus of the ×40 objective. The mineral showing white birefringence in XPL is in the same optical orientation in all the dendrites; however, the white mineral is too small to be able to determine an optical figure (and probably the orientation is also wrong). This mineral is not inconsistent with quartz, but microprobe analysis of its elemental composition would be needed to identify the mineral species.

Figure 1 Photomicrograph of part of an olivine within a very coarse clinopyroxenite, viewed in PPL. The flat dendritic structures are being viewed approximately face-on (×20; field of view 0.95mm.



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Discussion

Putnis and McDonnell (1980) discuss the process of forming these exsolution structures in olivine. They present a diagram (their fig. 8.24) of equilibrium positions of the products of oxidation/reduction reactions as a function of fugacity of the magma and its temperature. In the case of olivine with 5% fayalite at lower temperatures and fugacities the exsolution product is magnetite + silica (equation 1 being a plausible representation of the reaction), and at higher temperatures and fugacities the product is magnetite + pyroxene (equation 2).

$$6MgFe^{2+}(SiO_4) + O_2 = 2Fe_3O_4 + 3SiO_2 + 3Mg_2(SiO_4) \quad [1]$$

$$6MgFe^{2+}(SiO_4) + O_2 = 2Fe_3O_4 + 3Mg_2(Si_2O_6) \quad [2]$$

These exsolution reactions are discussed in more detail in Deer *et al.* (1997).

Using electron microprobe techniques Moseley (1984) found vermicular planar laminar intergrowths of magnetite-rich spinel and pyroxene in eight different olivine samples from various places. The intergrowths were found "on the close-packed (100) planes of olivine". He was also able to measure the chemical composition by electron microprobe both of the spinel and the pyroxene phases, and also of the host olivine. In most cases the spinel is mainly magnetite, but some contained appreciable amounts of SiO_2 and MgO. In all cases the pyroxene phase contained *c.* 20% CaO, making it a clinopyroxene. This Ca must have been scavenged from the bulk of the olivine because the host olivines often contain no measurable CaO.

Recently Khisina and Lorenz (2015) have suggested that these intergrowths may be due to postmagmatic dehydrogenation of humite minerals.

In the present work, and also in the photomicrograph of dendrites published by Teagle *et al.* (2012), the matrix of the host olivine shows a mottled appearance, as is also suggested in the pen and ink sketch published by Putnis (1979). This may indicate a pervasive alteration.

The author is not aware of any published reports of the optical detection of pyroxene or silica in photomicrographs of olivine exsolution dendrites. In the present work the similar appearance of the olivine in XPL outside the cartouches and within the broad magnetite cartouches (not illustrated) is probably because the accompanying ex-solved mineral is too thin to observe. A thickness of *c.* 0.3µ was measured by Moseley (1984), which would be too thin to change the optical properties of olivine in a thin section of 30µ thickness.

The bright white birefringence within the dendrites viewed nearly edge-on in this work, does not suggest a clinopyroxene; but quartz would be consistent with this.

Conclusion

Within the olivine crystals of a coarse olivine pyroxenite a rich array of small dendritic cartouche-like exsolution structures was found, which, when viewed almost edge-on, are intimately associated with a colourless mineral not inconsistent with quartz.

Acknowledgements

The author thanks Jessica Till, Giles Droop and David Moseley for helpful background information and useful references.

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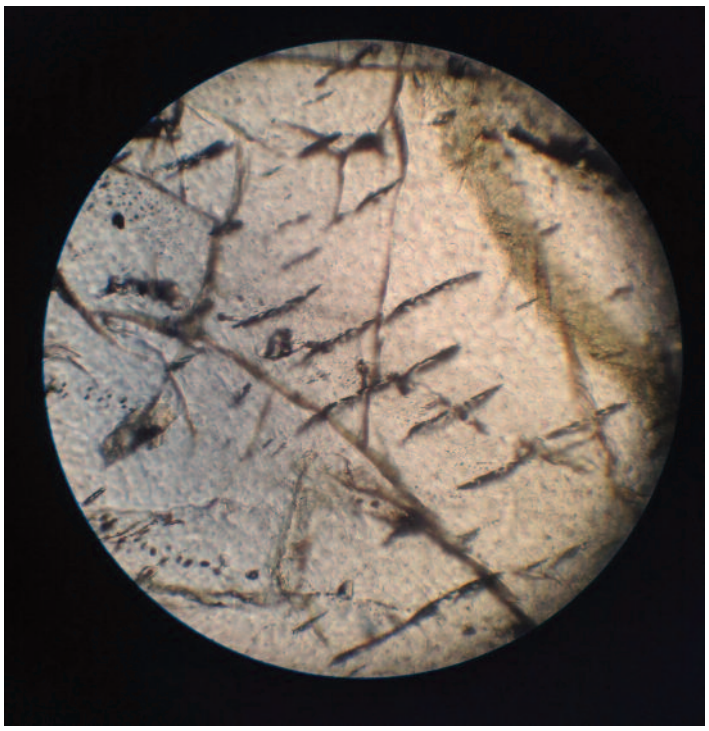

Figure 2 Photomicrograph of part of an olivine where the dendritic structures are narrow, viewed PPL, approximately edge-on (×40; field of view 0.5mm).

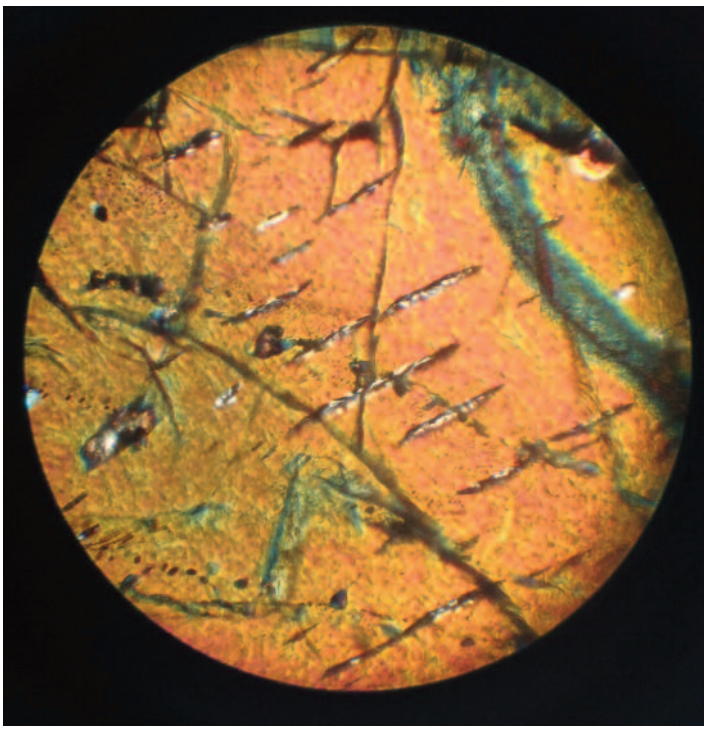

Figure 3 Photomicrograph of part of an olivine where the dendritic structures are narrow (Fig. 2), viewed in XPL, (×40; field of view 0.5mm).

Book review

Fastovsky, David E., and Weishampel, David B. 2016 *Dinosaurs: A Concise Natural History* (3rd edn). Cambridge UP (ISBN 1-316-50115-3; 477pp; paperback £44.99)

This book first appeared in 2009 and the issue of the 3rd edition in 2016 is the result of the very rapid increase in knowledge of dinosaurs, driven by the many exciting discoveries and ideas that have shaped our understanding in recent years. New discoveries and interpretations are being made regularly, so the issue of this 3rd edition is the latest attempt to keep up-to-date and to present the study of dinosaurs in the language and methods of professional palaeontologists.

The number of known dinosaurs has roughly trebled since 1980, with new species being discovered and new advances introduced such as the colour of feathers. This book is written for undergraduates and introduces the logic of scientific enquiry and concepts in natural history and evolutionary biology. It aims to help students achieve a creative synthesis of all data regarding dinosaur science.

Unlike other dinosaur books, Fastovsky and Weishampel use phylogenetic systematics instead of lists of names, dates and places. Cladograms are drawn to highlight evolutionary relationships they predict. This is a main feature of the book.

The book is organised into 16 chapters, divided into four parts, together with a glossary, credits and two indices. Chapters are arranged with stated objectives, easily read text, numerous clear illustrations, and boxes that contain ancillary topics. Each chapter ends with a summary and a list of selected readings, including recent publications; and a comprehensive list of questions.

Part I introduces the fundamentals of dinosaur palaeontology.
Chapter 1 deals with fossils and preservation, and with finding and preparing fossils.
Chapter 2 discusses geological time, continental drift and climate in the age of the dinosaurs.
Chapter 3 introduces phylogeny, evolution, phylogenic systematics and cladograms.
Chapter 4 discusses tetrapods in general and the place of dinosaurs in the classification.
Chapter 5 introduces the origin and early life of dinosaurs.

Part II is concerned with the major clade Saurischia.
Chapters 6, 7 and 8 discuss the meat-eating Theropods in detail, including the evolution of birds.
Chapter 9 is concerned with the plant-eating Sauropods.

Part III deals with the Ornithischia: armoured, horned and duck-billed dinosaurs.
Chapter 10 covers the armoured Thyreophorans, particularly Stegosauria and Ankylosauria.
Chapter 11 introduces Marginocephaphalia ,with their bumps, bosses and beaks.
Chapter 12 covers the herbivorous Ornithopoda, the most diverse and longest-lived of all Dinosaura.

Part IV covers dinosaur palaeobiology in three headings, and a history of ideas.
Chapter 13 introduces their metabolism.
Chapter 14 covers the rhythms that drove their evolution.
Chapter 15 covers the history of dinosaur palaeontology.
Chapter 16 gives an up-to-date explanation of their extinction.

Dinosaurs are big business, with many books and other media available to suit all tastes. A quick search for 'dinosaurs' on the ScienceDaily website returned 107,000 results. The book is a thorough introduction to the natural history of dinosaurs. It is well written and illustrated, and is accessible to undergraduates and dinosaur enthusiasts.

— Phil Robinson, BSc (Hons)

Book review

Cope, John C. W. 2017 *Geology of the South Devon Coast.* London: The Geologists' Association (ISBN 978-0900717-91-8; 122pp; £9.00 GA Members, £12.00 Non-members)

This is the latest field guide from the Geologists' Association and, in the words of the author, follows the plan of his recent Dorset Coast guide (also from the GA). To all intents and purposes it is an extension westwards of that guide, though of course it is complete in itself. It usefully covers the Devon Riviera Geopark.

After placing South Devon in a regional geological context, the succession is described in detail, as in the Dorset guide. There is no separate chapter on structure, which is a pity; however, relevant structure is covered in the body of the text.

There follow six itineraries, 36 localities in all, including eight inland to cover features not seen on the coast. The coast localities are more or less continuous, from Saltern Cove, just south of Torquay, to Pinhay Bay, west of Lyme Regis. They are arranged in ascending order of succession, which sometimes means backtracking along a route.

The text is concise and the geological detail remarkable, a clear result of the author's 60 years experience of field trips in this area. Interpretations are discussed and fully referenced.

Diagrams are not as extensive as in the Dorset guide, and the stratigraphic columns found there, are lacking in this South Devon guide. Nevertheless colour geological maps for most areas are included, as are colour photographs of practically all of the localities. The outline location maps are sufficient to find your way around, and six-figure references are always included, along with a host of practical details regarding accommodation, access instructions (including whether suitable for coaches), and the inevitable hazards and locations of mudslides, cliff falls, rifle ranges and the like. I particularly appreciate the injunction to wear your hard hat while eating sandwiches, to guard against the increasingly aggressive gull population. That's definitely going down on my next field hazard sheet.

The author points out that there is a dearth of comprehensive field guides for this area and he hopes this will fill that niche. This is a gem of a field guide, indispensable for anyone exploring this part of the coast.

I apologise for the many references to Cope's Dorset Guide, which I can't find reviewed in the *OUGS Proceedings*, but I'm sure many readers will know it. If you don't, buy that as well!

— Phil Ridley, BSc Hons Geosciences (Open), FGS

If at first you don't succeed…!
A possible meteorite crater at Kaş, southern Turkey

Alison Ure

Figure 1 Five Islands dive site Kaş Bay (reproduced by kind permission of Dave Talbot © 2016).

Introduction

This is the story of how a graduate student at the Open University (OU) went on to make a scientific discovery, almost by accident. I first came up with my idea seven years ago in 2011, with many people thinking I was mad. Since then I have had delays, setbacks, almost gave my theory away to someone else to pursue, been unsure of the direction forward, and questioned my findings with increasing lack of confidence, until finally publishing my first paper in March 2017 to secure my discovery. I hope that by reading this account I will encourage future graduates, or students, to keep going with an idea, even when they do not know in which direction they are going, how or why.

The beginning

In 2004 I bought a property in Kaş, southern Turkey, as a holiday home. I had recently learned to scuba dive and this beautiful idyllic part of the world was also the best place to dive in Turkey. Much of the diving occurred in and around a circular group of islands, known as Five Islands, where the underwater topography provided diving both for beginners and advanced divers (Fig. 1). This is a relatively shallow, dish profile — 20m deep — between the islands. It has a diameter of *c.* 1km, with steep drops around the edge, effectively an underwater upturned cone (Figs 2 and 3). As the general geomorphology of the area surrounding the town has concentric features, I assumed, as did many others, that they are the remnant of an extinct volcano (Fig. 4, *overleaf*). Across the bay from Kaş lies the small Greek island of Kastellorizo, which has steep cliffs similar to those seen on the mainland around Kaş (Fig. 5, *overleaf*). Could these be the walls of a volcanic crater?

I began my OU degree in Earth and Environmental Science in 2007, and in the autumn of 2010 I decided I wanted to learn more about the geology of this southern region of Turkey. In my role as event organiser for the Open University Geological Society (OUGS) South East branch, I set about researching the area with a view to organising a geological and archaeological field trip to it. I purchased a small booklet written by Jill Eyres (2004), entitled *Archaeology and Geology of Lycia, Southern Turkey*. From this booklet I gleaned information about the general area, also known as the Teke Peninsula and Lycia, and discovered that the

Figure 2 (left) 'The Canyon' dive site, showing its steep drops.(right) Figure 3 'The Canyon' at greater depth.

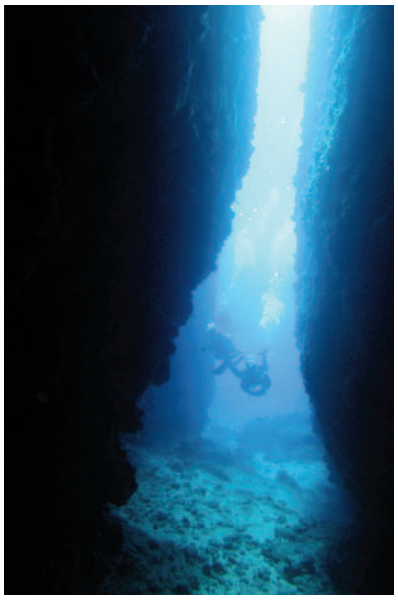

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Figure 4 Google Earth Image of Kaş Bay, showing its concentric features.

central belt, where Kaş was situated, was limestone. This information contradicted the theory of the 'Kaş volcano'. I was left with the question in my mind as to what else creates a cone shape in geology?

In September 2011 I started a module of my degree called 'Science in Context'. One of the subjects covered was Near-Earth objects and the impact hazard (Ball *et al.* 2007). As I read the chapter in the textbook on the evidence for meteorite impacts, I felt I recognised much of what was described and thought I had seen similar evidence around Kaş, particularly in the upturned cone shape of a central peak found in a complex crater (one with a diameter greater than 1.5km). One of the authors of this textbook is Professor Simon Kelley, whom I had met the year before at Malham Tarn on an Environmental Science residential course. I e-mailed Prof. Kelley describing my findings and asked what I should do next. He suggested getting some thin sections made, to look for microscopic evidence of an impact. I had absolutely no idea how or where to get this done.

I ran the OUGS field trip to the Teke Peninsula successfully in 2012, even though the Turkish leader, a last-minute replacement, spoke no English. I decided to run it again in 2014, this time with an English-speaking leader, but wondered who would be a suitable leader? A good friend and fellow student, Jane Stevens, saw a write up from a Geology Association field trip to Eastern Turkey led by Professor David Bridgland of Durham University, and suggested I contact him. So I did. Prof. Bridgland agreed to lead the next trip with his friend and colleague Dr Robert Westaway, a Research Fellow at Glasgow University. In October 2013 I went to Durham University to meet them and discuss the upcoming trip. I had an ulterior motive, of course! After going through the itinerary, I started explaining the evidence I had found out about the topography around Kaş, and before I had finished Prof. Bridgland said, "You think there has been a meteorite impact there?" My simple answer — as I handed him several rock specimens I had collected — was "Yes, and can you get these rocks made into thin sections please? I've waited two years to find someone who could do it?" Dr Westaway immediately offered to take them to Glasgow University to the rock preparation technician.

My 'mad' theory had begun to take shape!

The middle

Dr Westaway sent the thin sections to me in May 2014 and I, in turn, sent them to Prof. Kelley to analyse. He returned them a few weeks later with a full report of very nice fossiliferous limestone. Initially I was disappointed but then I started thinking about it logically. Just because there was no evidence in these thin sections did not mean there was no evidence, it just meant I had the wrong samples; it was 'back to the drawing board'.

In October 2014 I started looking for more evidence and found unusually brecciated rock in a number of places around Kaş. Furthermore, some of the rock had what appeared to be a flow texture, almost as if it had melted and then recrystallised as calcite (Fig. 6, *opposite*).

I had read about impact breccia and wondered if this was it? Equally, could it be slope-deposit breccia, resulting from the many earthquakes in the area (Fig. 7, *opposite*)? My friend Jane Stevens, who was staying with me at the time, went back to the UK via Kastellorizo and excitedly told me she had seen similar brecciated rock on the Greek island (Fig. 8, *opposite*). Was this a coincidence or was there just a lot of slope-deposit breccia in this highly tectonic area?

I collected some brecciated samples from around Kaş and brought them back to England hoping for better results from the thin sections they produced. Again, I sent the thin sections to Prof. Kelley, but again there proved to be a disappointing lack of evidence of impact-created breccia.

I graduated at the OU in June 2015 and doggedly refused to give up my theory, even though I seemed to be going nowhere fast, and was even less sure of my next direction. It was the

Figure 5 The steep cliffs on Kastellorizo.

Figure 6 Brecciated rock with some flow texture and recrystallisation, mainland Turkey.

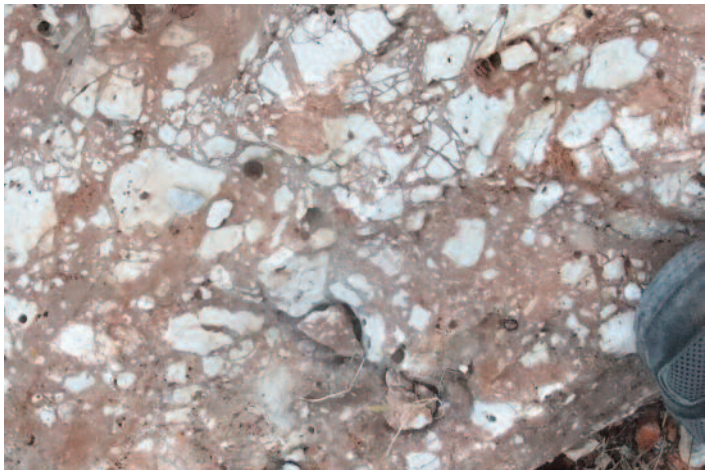


Figure 7 Mainland Turkey — impact breccia or slope deposit breccia?

underwater cone that intrigued me. What geological process or processes had created it? If it was not a volcano then surely it had to be an impact structure?

In October 2015 I was back in Kaş and started logging the sites of the brecciated rock, both around Kaş and on Kastellorizo, believing that they could possibly be impact breccia.

In November 2015 I returned to Durham, where Dr Westaway introduced me to Brigitte Vogt. She was doing her PhD at Strathclyde University in Glasgow and was planning on doing further research on different impact craters. Dr Westaway had mentioned my theory to her and she was interested to meet me. I showed her what evidence I had so far, and we discussed what further evidence was needed. Shatter cones came up in the conversation and she produced one she had found on a field trip to Germany. We discussed her taking my project on as I felt I had taken it as far as I could. During this visit to Durham, with help from Dr Westaway, I applied for the 2016 Open University Ian Gass Bursary, with reservations.

In February 2016 Brigitte informed me that she was changing her research subject so would no longer be able to take over my project. In March 2016 I was stunned when the Ian Gass Bursary Committee contacted me to say I had been awarded the bursary. I had expected it to be laughed out of the application process, hence my reservations, and was now very glad I had not given my project over to Brigitte. My first thought, when I had got over the shock, was, "Now I have to be a real scientist. Where do I start?"

Research: that is always a good place to start, and up to that point in my geological studies I had done very little. So I started reading and researching, beginning with a wonderful book by Kathleen Mark (1987), entitled *Meteorite Craters*. In this book she recounts the fascinating and sometimes highly controversial detective story of how scientists came to recognise meteorite craters.

In April 2016 I ran another OUGS trip to Turkey, again led by Prof. Bridgland and Dr Westaway. They wanted a week in Kaş before the trip to do some research fieldwork of their own on river terraces in a valley inland from Kaş. I was their driver, picnic maker and stone collector, which gave me a great opportunity to watch and learn from two experts in action in the field. I had not managed to attend any geology residential trips while studying for my OU degree, so had never actually done any fieldwork! What I learned from Prof. Bridgland and Dr Westaway that week was invaluable to me later that year. I also took them to a couple of my sites and they both agreed something catastrophic had happened in the area, which was not easily explained by normal geological processes.

In June 2016 it struck me as a good idea to go and visit a known impact site to see one for real. So I went to Germany to visit the Ries Crater and its museum, and the nearby smaller Steinheim Crater. It was at this latter crater that Brigitte Vogt had found the shatter cone she had showed me in Durham. The Steinheim Crater's topography had similarities to Kaş: in size, having a central peak and being limestone. I was also able to speak to the resident geologist, Dr Stephan Holtz, of the Ries Crater museum, about my project and the reason for visiting the area. He confirmed what Brigitte Vogt had said, that shatter cones would be good to find, especially in a limestone crater, as they were the

Figure 8 Brecciated rock on Kastellorizo.

Figure 9 Matrix supported breccia, mainland Turkey.

only macroscopic definitive evidence for an impact structure, microscopic evidence in carbonates being less easy to interpret. I was learning a lot, but also becoming increasingly frustrated with what I was researching.

Much of the microscopic-specific criteria I had learned that I needed to find as definitive evidence is related to impact sites in crystalline rocks or siliciclastic sediments. Here the impact signature of high temperature and high pressure in the silicate minerals is clearly defined as 'planar deformation formations' (PDFs), for example in quartz, along with diaplectic glass. However, this sort of 'signature' was not helpful to me searching an impact site on thick carbonate rock. In addition, the fact that most of my crater, particularly the central peak where shatter cones might lurk, was underwater, half in Turkey (Asia) and half in Greece (Europe), and also in a highly tectonic zone, it was not easy working out what I could expect to find that could be definitive.

I tried contacting several experts who had experience with carbonates but, frustratingly, got no response from any of them. I felt that I was floundering my way in the dark; and when I went to Kaş in October 2016 to carry out my bursary fieldwork I still did not really know what I was looking for, and whether I would recognise it if I found it. A friend and fellow OUGS South East committee member, Dave Talbot, came with me for the first week, and together we walked the locations I had covered the previous year and extended them. Over the next two weeks

Figure 10 Clast supported breccia, mainland Turkey.

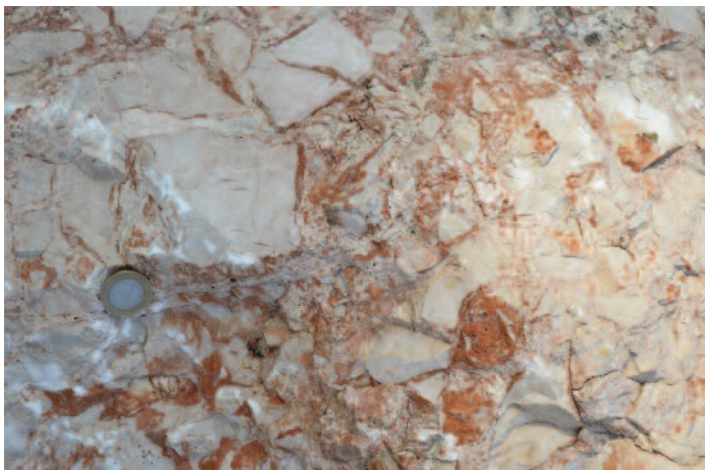


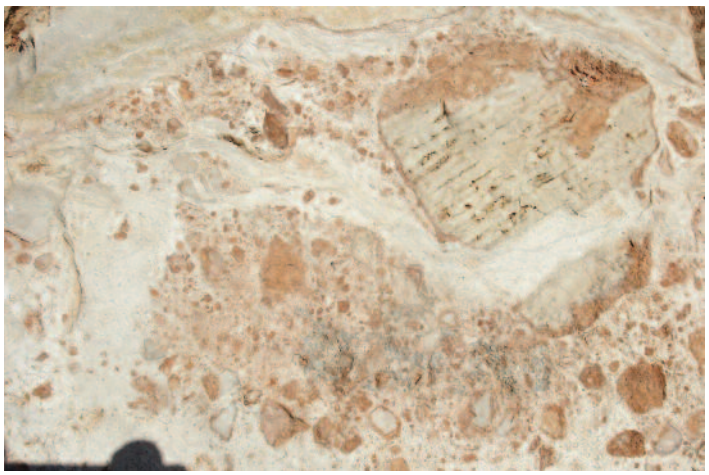
Figure 11 Large limestone boulder, c. *1m long, surrounded by very fine breccia, Kastellorizo.*

I covered as much ground as I could, visiting Kastellorizo three times. I took more than 300 photographs and logged sites of the unusual brecciated rocks in my trusty notebook, recording their GPS references, as I had learned to do from Prof. Bridgland and Dr Westaway in the spring; and I collected still more samples.

While Dave Talbot was with me we both agreed that there was evidence that something inexplicable and catastrophic had occurred in the area, which appeared to have had a large amount of energy. Along with many different types of breccia, some matrix supported (Fig. 9), some clast supported (Fig. 10), and everything in between, there was also some breccia with large boulders of limestone that appeared floating in a matrix of much smaller clastic fragments (Fig. 11). Furthermore, there was some very odd-looking breccia (Fig. 12), and some that looked as if it had been plastered onto the country rock (Fig. 13, *opposite*), not a regular sedimentary sequence!

Dave Talbot was a great help to bounce ideas off, but after he left and I was doing fieldwork on my own again, I started to have doubts. We thought we had found evidence to point to an impact, but by the time I got back to England I thought maybe it was because we *wanted* to find evidence that we thought we had. I became so disillusioned that I did not download my photos for three weeks, and it was only because I had arranged to go to Durham to visit Prof. Bridgland and Dr Westaway again that I organised myself to present them with something.

Figure 12 Odd-looking breccia on Kastellorizo.



Having downloaded the photos and gone through them, my enthusiasm started to return. I was sure I had evidence pointing to a possible impact structure, but what I really needed was an expert in this field to analyse my findings — but who? I went to a website I had used for much of my research, Ernstson [and] Claudin (accessed 2017) 'Impact Structures — Meteorite Craters', and contacted one of the authors. Professor Kord Ernstson of the University of Würzburg responded to my e-mail within the hour and promised to look at what I had sent him, and to respond in full the following weekend. Three days later, on November 19th, he sent a long and thorough e-mail, giving me links to various sections that I had not previously visited on his website, and annotating my photographs either with explanations or with very similar photographs from other known impact sites.

Figure 13 Breccia 'plastered' onto country rock, mainland Turkey.

One particular piece of evidence was a phenomenon known as 'breccia-in-breccia' (Fig. 14), which I had never encountered, and which rarely occurs except in an impact structure. He described polymict and monomict breccia, which are breccia made from clasts of different material or clasts of the same material, and also breccia dykes (Fig. 15), again, none of which I had encountered before. Breccia dykes come in many sizes and are fissures in the country rock, caused by the impact, and subsequently filled with the brecciated material resulting from the impact.

It was his final paragraph that stunned me. He said he was so convinced I had discovered a new impact structure, that I should publish an abstract paper at the Lunar and Planetary Science Conference (LPSC) to be held in Texas in March 2017 before someone else took ownership of my discovery. Over the next few days I sent Prof. Ernstson more photographs and asked more questions, to all of which he responded promptly and positively. After a week of communication I thought it a good idea to check his credentials, though he did seem to know what he was talking about. It turned out he had done his PhD on the Ries Crater in 1976, was a geophysicist as well as a geologist and had studied rock fracturing and impact craters, among other geological structures and processes, for 40 years. He was, and still is, the expert I needed to help me.

The end

My next daunting task was to write the abstract paper. Thankfully I knew that Prof. Bridgland and Dr Westaway would be able to help me when I went up to Durham to see them the first week of December. I looked at other papers published at the LPSC and followed the format, putting together my first draft. This I presented to Prof. Bridgland and Dr Westaway, who proceeded to mark it like an OU TMA! With their input and further input from Prof. Ernstson the paper was submitted, accepted and published at the end of March 2017.

Figure 14 Breccia-in-breccia, mainland Turkey.

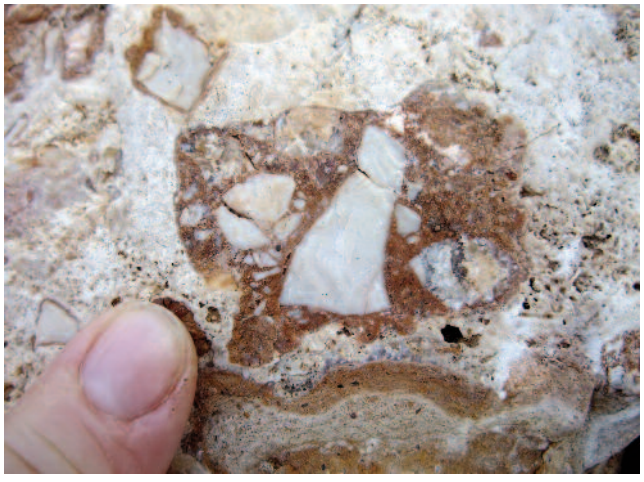


Figure 15 Breccia dyke on Five Islands.

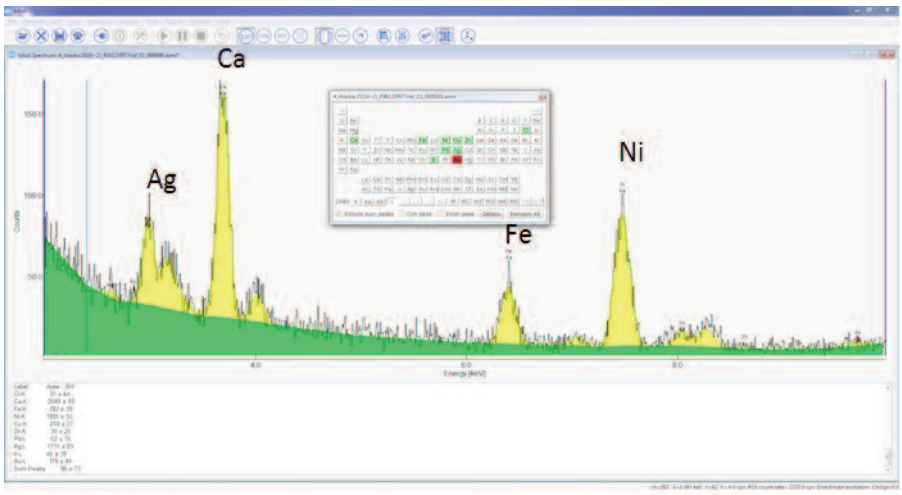


Figure 16 Screen shot from Baxil software XRF trial. The nickel (Ni) spike on the right of the figure shows mineral content levels between the iron (Fe) and calcium (Ca). The silver (Ag) spike on the left is irrelevant and connected to the equipment used.
[Note: as a digital 'screen shot', its resolution could not be improved — Ed.]

Actually, this is not the end of my story; it is more like the beginning. As well as preparing the paper, I also spent a couple of days in the laboratory at Durham University, thanks to Prof. Bridgland's influence, looking at more thin sections from samples brought back in April 2016. Several showed multiple twinning in calcite, which could be the result of an impact, though it could also be due to tectonics. The wonderful laboratory technicians also ran magnetic susceptibility tests on a few of my samples, as well as X-ray fluorescence to detect the mineral content. Both of these tests threw up interesting anomalies, such as the matrix in the breccia being strongly magnetically susceptible (Table 1, *below*) — a common feature in known impact structures — and one of the mineral spikes showing an unusually high content of nickel (Fig. 16). Further investigations on more samples will indicate if either of these findings is significant, but they are certainly unusual in a carbonate matrix.

One of the requirements of the Gass Bursary is to educate the community where the project took place, about the content of the project. This I intend to do in the form of a storyboard and I felt that a few basic facts might be a good idea, such as age, size, speed of impactor, and energy released.

Using the age of a known fossil bed inland from Kaş, visited during Prof. Bridgland and Dr Westaway's fieldwork in April 2016, and working out uplift and subsidence rates, we reached the conclusion that the impact occurred during the Pleistocene Epoch. Brigitte Vogt had sent me a publication on the traces of catastrophes (French 1998), which included a useful table with sizes of impactors and the energies released by them based on the diameter of the craters they made. Kaş Bay is *c.* 10km across, so the meteorite that created its crater would have been *c.* 500m in diameter, travelled at up to 70km/s, and would have released energy the equivalent of *c.* 11,000MT of TNT. The atom bomb dropped on Hiroshimo, Japan in 1945 was *c.* 20KT, so the Kaş meteorite would have been a big bang!

In April 2017 I returned to Kaş for a week with new eyes, seeing more in the rocks than I had seen before and being able to begin to read their language, which was the main reason I took my geology-based degree in the first place. I spent two days with Professor Tuncer Demir from Antalya University — Prof. Bridgland and Dr Westaway had introduced us the previous April, as Prof. Demir had done his PhD with Prof. Bridgland at Durham Univesity and had worked on many projects in Turkey with them both.

Prof. Demir was very helpful as a geomorphologist looking at the bigger picture, and it was good to have someone again to bounce ideas off. I collected more rock samples to bring back to the UK, and just before I left Kaş I had a brainwave. Shatter cones had not been forthcoming in any of my fieldwork, mainly because of their location around the central peak. I had looked when visiting the small islands but I had not found any. As the central peak was mainly underwater, I spoke to a great friend and diving instructor, who knew all about my project, and asked if there was a chance of getting a number of divers to carry out citizen science research over the coming season and look for shatter cones underwater? She agreed, and this is being done as I write this article — and hopefully they will find some evidence.

In May 2017 I once again visited Durham and spent a couple of productive days in the laboratory. Still no definitive microscopic findings: that particular needle in the haystack, or in my case grain of sand in the limestone, is still elusive. I was able to do more reading and research during the train journey to and from Durham, and going through my photographs again I discovered that I had found more than I originally thought in October 2016, but had not been able to see it at the time. Some of the new set of thin sections taken from the samples collected in October 2016 threw up several interesting anomalies too.

Along with the geomorphology of the area and the impact breccia previously seen, I now had evidence of what appeared to be melting and decarbonisation, both indicative of the high temperatures associated with impacts; and of breccia dykes of various sizes, one of which could possibly be described as an impact pseudotachylite; and possible accretionary lapilli, both in macro and microscopic form. This last phenomenon is usually associated with volcanic eruptions but is also found in impact structures.

Table 1 Magnetic susceptibility trial test

specimen	*magnetic susceptibility (×10-^{5} SI)*	*brief description*
RW 11	3.4	limestone with some matrix in fractures
RW 12	108.5	some limestone in matrix
RW 13	3.3	limestone with some matrix in fractures
RW 14	81.9	some limestone in matrix
RW 15	–1.4	limestone, no matrix

Conclusion

The fieldwork carried out to date has built a strong argument in favour of Kaş Bay having been formed by a meteorite impact within the last 2.5 million years; however, I still have to find the elusive evidence that will conclusively prove this hypothesis. My research will continue if I can find a source of funding, and if the impact can be definitively proved, Kaş could become the second UNESCO geo-park in Turkey, their equivalent of an SSSI.

I did a degree with the OU for fun, never thinking for one minute it would lead to a scientific discovery and a published paper (Ure *et al.* 2017).

I am not sure where this project will end up but so far it has been a huge learning curve that has been exciting, interesting and often frustrating. If any of you readers get a crazy idea, follow it up, you never know where it might lead.

Acknowledgements

I would like to thank the Ian Gass Bursary Committee for believing in me and for giving me this wonderful opportunity. I consider myself incredibly lucky to have found the right professionals to support me: Prof. Bridgland, Dr Westaway, Prof. Ernstson and Prof. Kelley, without whom I would definitely not be writing this article for the *OUGS Proceedings*. Many thanks go to laboratory technicians Neil Tunstall and Eleanor Maddison for their ongoing help in the Durham University laboratory, as well as to numerous friends both in England and in Turkey who have supported me from day one. Many, many thanks to all of you.

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Addendum

As this article is going to print a second abstract paper strengthening the meteorite impact hypothesis and making Kaş Bay a probable impact structure has been submitted to the 2018 LPSC.

Editor's notes to contributors

Following are guidelines for the submission of articles to the *Proceedings of the OUGS*. The principal theme encompassed within these guidelines is 'please keep it simple'. Let your editor do his job and please do not try to simulate, emulate or reproduce the page layout of the *Proceedings*. I have dedicated page-layout software (QuarkXPress) to do this and any special formatting, special characters and embedded illustrations that you include in a word-processing document can be lost (at best) or seriously confuse and crash (at worst) my iMac or the QuarkXPress software when I import it into the layout.

If your article contains special characters (such as mathematical symbols), please draw these to my attention — I will probably spot them anyway — so that I can import them properly with the glyphs menu in QuarkXPress.

Here are the basic guidelines. I will contact you about any queries that arise when I read your article. I will send you an edited version, showing you any changes that I have made and raising any queries or requesting any missing information.

Guidelines for *OUGS Proceedings* articles

As *OUGS Proceedings* Editor I do not want the publication of your article to be more work than is necessary for you (or for me!). Your article need not be more than about 1,500 to 4,000 words in general, but I leave the length up to you to suit the material you are writing about.

Regarding articles from the presenters of lectures at the OUGS AGM and Symposium, all OUGS members are grateful to you for presenting a lecture to us on your research, and for agreeing to submit a version of your talk for publication in the *Proceedings*. The purpose of this is to make your information available to OUGS members and others who could not attend the symposium. As OU students and OUGS members we enjoy hearing and learning the information these events bring to us.

All that is necessary are:

• A Word (or compatible) file of the text: There is no need for you to attempt to format the text in any way using tools in Word or other word-processing software. I will do the page layout format in the *Proceedings* house style, using dedicated publication-industry-standard page-layout software (QuarkXPress). However, feel free, if you wish, to use **bold** and/or *italics* to indicate headings and subheadings so that I can identify and set these into house style.

I do not require a hard copy, but if you need to point out special characters or attributes in your article, it may be a good idea to send one with these items marked up or otherwise highlighted. I can accept electronic files attached to e-mails, text and image files on a CD or on a flash drive, or via shared media.

• Each illustration, chart, graph, map or other illustration as a separate digital file in high resolution: 300dpi minimum for colour or half-tone images; as high a dpi as possible, please, for line illustrations. Tables composed in Word or Excel are fine, as they are just text. A rough guide to the number of figures in an article is 10 to 30. Obviously as an AGM or symposium presentation speaker you might have shown numerous slides, so please use your best judgement on the number to publish with your article — again, usually 10 to 30 is only a rough guide.

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Dr David M. Jones, *OUGS Proceedings* Editor, 41 Blackburn Way, Godalming, Surrey GU7 1JY; 01483 424308;
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OUGS Moyra Eldridge Photographic Competition 2017

Winning and Highly Commended photographs

Geologically inspired landscape structure or feature in the British Isles & Popular vote, Winner — Ian Williamson

Carsaig Arches, Mull, NW Scotland. Geology and coastal geomorphology combine at Carsaig Arches. Situated below Malcolm's Point south-west of Carsaig Bay, these impressive natural arch formations are the result of on-going coastal erosion processes acting upon on a sequence towards the base of the mid-Palaeocene Staffa Lava Formation (Hebridean Igneous Province). The photograph shows columnar-jointed lavas and inter-volcanic sedimentary rocks, their combination emblematic of the Formation, intruded by a dolerite thick sill.

Geologically inspired landscape structure or feature, British Isles, Highly Commended

Tracy Atkinson

The Quiraing, Trotternish, Isle of Skye. The Quiraing is an area of rotated landslip blocks, which have detached progressively from the escarpment as the weaker mudstones at their base failed because of the weight of the more competent overlying Palaeocene lavas. The resulting landscape is one of high cliffs, buttresses and pinnacles.

Sandra Morgan

Limestone slopes of the Eglwyseg Escarpment and Offa's Dyke, Llangollen. The Eglwyseg Escarpment is situated about a kilometre and a half north of Llangollen, and its slopes rise dramatically above the town. The Carboniferous Limestone scenery of the Escarpment is accessible to walkers on the Offa's Dyke Path. Among the scree that covers its scarp slope, fossil brachiopods and corals can be found. The Carboniferous Limestone is part of the Clwyd Limestone Group, which is *c.* 330myr old.

Geologically inspired landscape, structure or feature anywhere else in the world, Winner — Kath Addison-Scott

Cross-bedding in Navajo Sandstone, Zion Nationa Park, Utah. Wonderful examples if large-scale cross-bedding in Jurassic Navajo Sandstone. The sandstone was deposited as sand dunes, blown by north and north-west winds, in the Navajo Desert *c.* 200 million years ago. This desert was larger than today's Sahara.

Geologically inspired landscape structure or feature, elsewhere in the world, Highly Commended

Kath Addison-Scott

Checkerboard Mesa, Zion National Park, Utah. The mesa is of Jurassic Navajo Sandstone, which was deposited as sand dunes in the Navajo Desert *c.* 200 million years ago. The desert was larger than today's Sahara. The face of the mesa is criss-crossed with horizontal cross-beds and vertical jointing. The jointing was probably caused by expansion as erosion reduced the weight of the overlying rock.

Anna Saich

Flysch beach, Basque Coast Geopark, Spain. Basque Coast Geopark, Spain: Spectacular sub-vertical turbidite (flysch) beds on the beach at Zumaia.

Industrial geology, Winner — Mellissa Freeman

Torrin Marble Quarry, Skye. The Torrin Marble Quarry is on the road just before you arrive at Camas Malag, Salye. White limestone is quarried here.

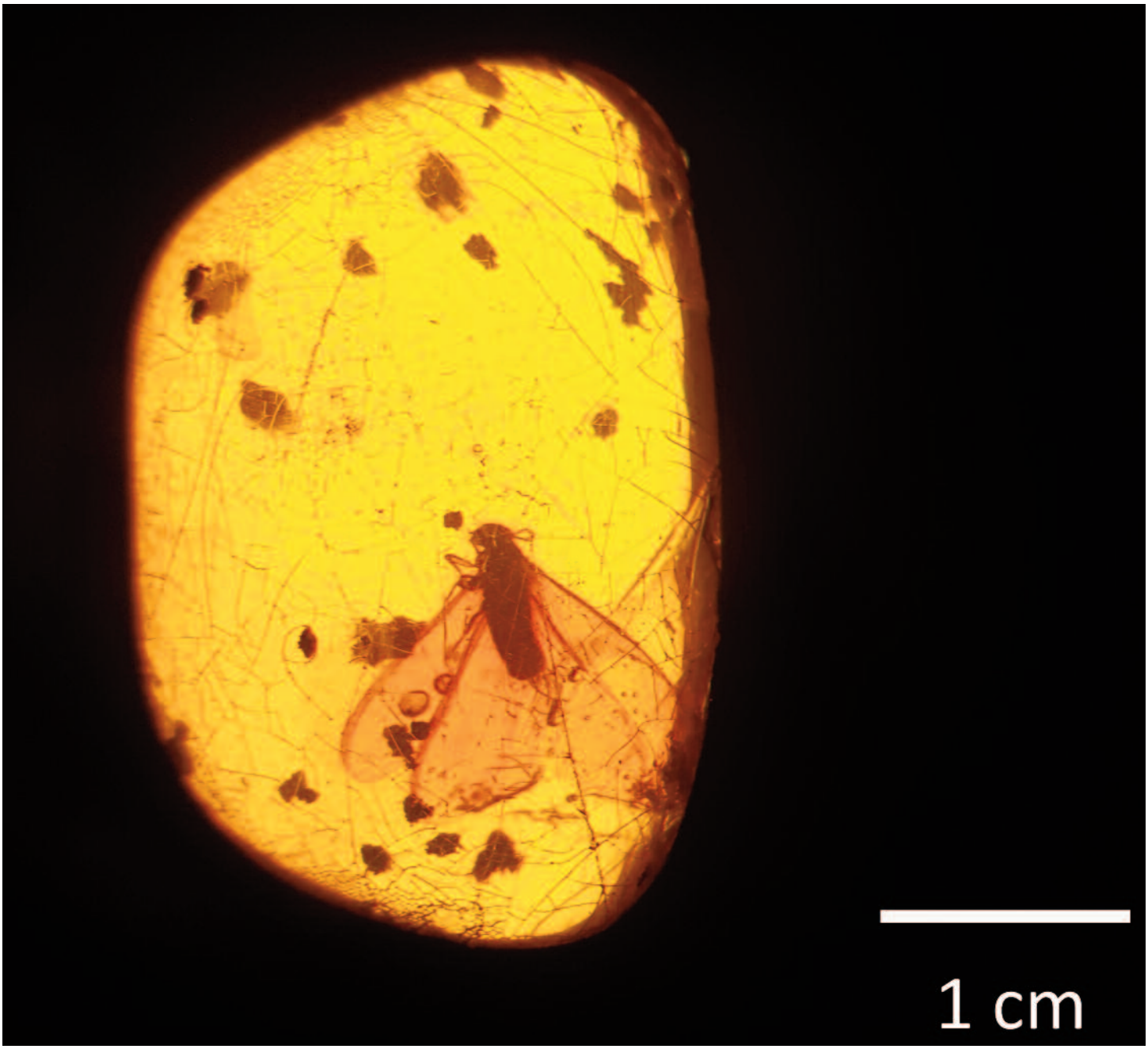
Industrial geology, Highly Commended

Sandra Morgan

Parys Mountain copper mine, Anglesey, Wales. Minerals found at Parys Mountain derive from metal sulphides deposited 440Ma by submarine volcanic activity in the Iapetus Ocean. In the late 18th century, Parys Mountain was the largest copper mine in Europe (people for scale beside fence, top right). A major use of its copper was protective cladding for wooden British warships. Copper was initially mined near the surface, then by open-pit mining, and finally by underground shafts. The yellow, orange and brown colours derive from iron pyrites. Recent research has established that Parys Mountain was mined for copper in the Bronze Age, and significant deposits remain in the area.

Anna Saich

Kentish Ragstone. Hermitage Quarry, Kent, England. Alternating layers of Ragstone (limestone) and Hassock in Hermitage Quarry. Ragstone can be used as a building stone and the quarry adds value to the product by employing a stone mason to prepare the stone on site. The Hassock was previously considered a waste product but is now sold as a drainage material.



Mineral, rock or fossil specimen, or thin section/SEM view, Winner — Anna Saich
Wasp in amber. Copenhagen Amber Museum, Copenhagen, Denmark: Copenhagen Amber Museum has a fabulous collection, including many specimens with insects entombed within the amber.

Mineral, rock or fossil specimen, or thin section/SEM view, Highly Commended

Sandra Morgan

Crinoidal limestone from Salthill Quarry, Lancashire. Salthill Quarry is a Nature Reserve and SSSI near Clitheroe, Lancashire. It is a former limestone quarry and is now very important for both its geological formations and its wildlife. Over 300 million years ago in the Carboniferous period, the Clitheroe area would have been covered by a warm, clear sea. In this tropical sea, creatures called crinoids flourished. Carbonate from crinoids and algae makes up a substantial proportion of the limestone in this area.

Tim Walker

Peridotite thin section and camera mount. I was inspired by the BGS Project to digitise their archive collection of 190,000+ rock thin sections. Using my Canon 450D DSLR camera, fitted with the standard 18–55mm lens and a 12mm extension tube I captured the whole thin section. Despite not having a macro lens the image is reasonably sharp towards the edges. The slide was 'sandwiched' between polarising filters and backlit using a Kaiser LED lightbox. The camera was mounted vertically above the slide and fine focusing was achieved using a laboratory scissor jack. The peridotite slide contains olivine, twinned and normal zoned plagioclase feldspar, augite and chlorite.

Popular vote, Winner — Ian Williamson
Carsaig Arches, Mull, NW Scotland *(see above).*

Popular vote, Runner-up — David M. Jones
Wastwater Screes reflected, English Lake District. The ancient, glacially scoured lake of Wastwater in the English Lake District, formerly a fjord connected to the sea, is England's deepest lake (258ft; 79m). While the lake surface is now 200ft (61m) above sea level, owing to isostatic uplift, the bottom remains more than 50ft (15m) below sea level. And while its north-western shoreline rises more gently into the fells, its south-eastern shoreline is overlooked by the ridge if Illgill Head, whose north-western flank falls steeply into the lake as the dramatic Wastwater Screes, here photographed in the autumn, with orange bracken clinging precariously to niches in the screes.

Also
Anna Saich, ***Wasp in amber*** *(see above).*
Sandra Morgan, ***Limestone slopes of the Eglwyseg Escarpment and Offa's Dyke, Llangollen*** *(see above).*